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STRUCTURAL RELATIONS OF THE BUSHVELD IGNEOUS COMPLEX, TRANSVAAL[1]

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ABSTRACT

In the South African Bushveld the thick Waterberg system of sediments lies unconformably on the Transvaal system. The huge Bushveld igneous complex, composed of norite, pyroxenite, anorthosite (etc.), diabase, granophyre, and coarse granite, has long been supposed to be a differentiated laccolith, injected along the interface of unconformity. However, new field evidence shows that the Waterberg system is separated from the igneous complex by an important erosion-unconformity. The originally basic magma formed sills in the strata of the Transvaal system, but a large part of the magma broke through the whole Transvaal system and welled out at the earth's surface. This magma was differentiated and crystallized as norite (with pyroxenitic and other phases) and granophyre-felsite, both of which were later cut by dikes, sheets, and stocks of coarse granite, itself a late product of the same igneous invasion.

The Bushveld igneous complex illustrates: (1) areal (deroofing) eruption on a grand scale; (2) the floor relations of a lopolith characterized by satellitic intrusive sheets; (3) thoroughgoing differentiation, dominated by gravity. In general, the salic pole of the main differentiation had no roof, and solidified as dense or glassy felsite, passing downward into granophyre. Over much of the area the femic differentiate, norite-pyroxenite, had no roof other than the already solidified, upper, felsite-granophyre phase. The Waterberg sediments were deposited unconformably on the coarse granite, and, *a fortiori*, long after the solidification of the norite. This erosion interval is significant in the geological history of South Africa. Its recognition enforces the conclusion that the Waterberg system should include no beds older than the "Upper Waterberg" of the Geological Survey of South Africa.

INTRODUCTION

Of its kind the Bushveld igneous complex of the Transvaal is the largest and most remarkable yet mapped. A small part of it

[1] *Shaler Memorial Fund Expedition Report No. 13.*

remains to be mapped in detail, but already the map-sheets published by the Geological Survey of South Africa show the grandeur of this assemblage of rocks and the extraordinary amount of crustal displacement associated with their eruption. These maps illustrate eloquently not only the imposing facts of Transvaal geology but, as well, the skill and arduous labor of their authors—Hall, Kynaston, Mellor, Humphrey, and Wagner. Hall has mapped the greater part of the area, and it is to be hoped that he may be enabled to monograph the complex as a whole. Meantime, the close study of the Transvaal sheets, preferably mounted together, will specially repay every student of igneous rocks.

Though the edges of the complex have been frayed away by prolonged erosion, its (east-west) length is now about 500 kilometers, and its width at least 150 kilometers (Fig. 1).

The compound mass of igneous rocks has often been called a "laccolith," and also, recently, a "lopolith," a name which emphasizes the wonderful subsidence of the sedimentary floor (Transvaal system) on which the complex rests.[1] Yet accumulating evidence shows this vast body to be neither a simple laccolith nor a simple lopolith, but a group of igneous units which together may best, for the present at least, be called a "complex."

The lowest members of the complex consist of a number of thick and very extensive "diabase "sills, injected into the beds of the Transvaal system. The sills seem to be syngenetic with the largest single member, the well-known norite, which rests sheetwise on the Magaliesberg quartzite, the uppermost division of the Transvaal system of sediments. Closely associated with the norite are widely extended, sheetlike bodies of granophyre and felsite, which are chiefly developed within the outer boundary of the norite. Finally, all of the members just mentioned are cut by coarse red granite, occurring as dikes, sheets, and (probably) stocks. The norite shows differentiation in place, with the formation of layers of pyroxenite, peridotite, anorthosite, magnetite-rock, chromite-rock, and other types. The main body of felsite-granophyre magma seems to have been formed by gravitative differentiation, the norite magma representing the other pole. The magma of the coarse red

[1] See F. F. Grout, "The Lopolith," *Amer. Jour Science*, Vol. XLVI (1918), p. 516.

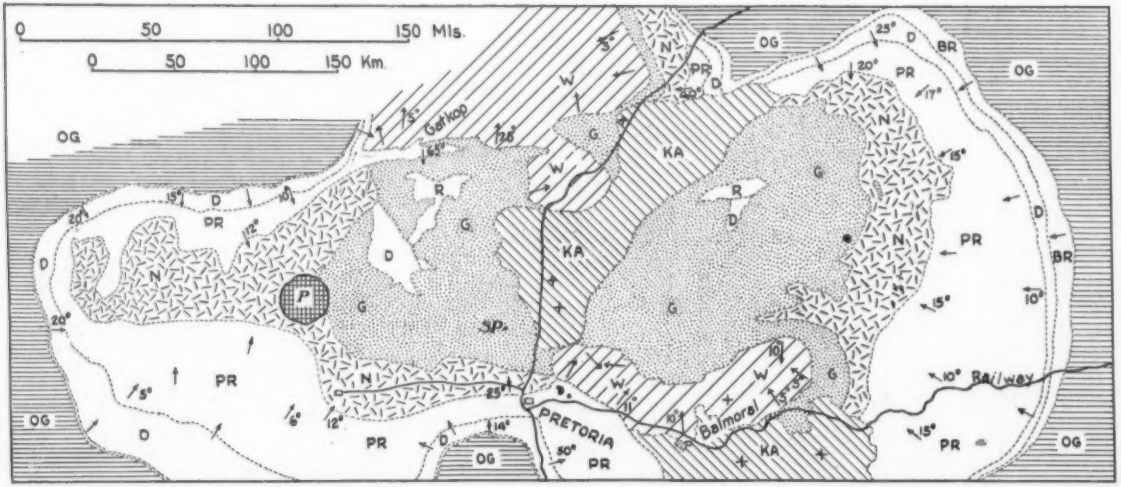


FIG. 1.—Sketch-map of the Bushveld complex. *KA*, Karroo system, unconformably overlying the Waterberg system; *W*, Waterberg system, unconformably overlying the Bushveld complex; *G*, felsite, granophyre, and granite of the Bushveld complex, the last younger than the norite; *N*, norite (with pyroxenite, anorthosite, etc.) of the Bushveld complex—like *G*, eruptive into the Transvaal system; *PR*, Pretoria quartzites and shales; *D*, Great Dolomite; *BR*, Black Reef quartzite (*PR*, *D*, and *BR* conformable members of the Transvaal system, which is unconformable on *OG*); *OG*, Old Granite chiefly—old pre-Cambrian complex; *P*, alkaline rocks of the Pilandsberg—three other small alkaline bodies shown in black; *SP*, Salt Pan caldera; centripetal dips of the Transvaal system shown, also typical dips in the Waterberg and Karroo systems.

granite, though younger than either and clearly syngenetic with norite and granophyre, must have been generated in depth, below the norite.

The famous group of highly alkaline rocks of the Pilandsberg, the associated great dikes of alkaline rocks, and the analogous bodies at Leeuwfontein, Spitskop (Sekukuniland), etc., may be genetically connected with the main norite-granophyre-felsite-granite mass, but all of the highly alkaline bodies are probably very much younger than even the coarse granite. For this reason, but particularly for convenience in discussion, the highly alkaline bodies are here excluded from the group called the "Bushveld complex."

The obvious importance of this colossal assemblage of igneous rocks to petrogenic theory prompted the writer (Daly) to organize a Shaler Memorial Expedition from Harvard University. The party consisted of Professors Palache and Daly, of that institution, and Professor Molengraaff, of the Technische Hoogeschool at Delft. The party was joined by Dr. F. E. Wright, of the Geophysical Laboratory (Carnegie Institution) of Washington. Special field studies were carried on during the first two-thirds of the year 1922. The geologists at Pretoria, particularly Messrs. Hall, Rogers, du Toit, and Wagner, co-operated with entire cordiality and helpfulness. Without their aid the visitors could not have studied many of the critical sections, which so illuminate the structure and history of the Transvaal. During the months of discussion and field-work the ideas of the whole group, hosts and visitors alike, were pooled, and it is almost impossible to assign the formulation of any of the new conclusions to a single member of the group. However, to simplify the bibliographical references of the future, it has been decided that in general not more than two names shall head published reports on the results of the mission, and that these reports shall be the responsibility chiefly of the visiting geologists. The following pages deal with only one of the many problems which engrossed the party, but for clearness it has seemed advisable to state some of the more general conclusions reached by the members of the joint expedition. It will be understood, therefore, that Dr. Palache and Dr. Wright are associated with the present writers in announcing these general conclusions. Further, both of these

geologists have helped materially to solve the special problem here considered, as hereafter noted.

This question concerns the relation of the Bushveld complex to the thick overlying series of sediments called the "Waterberg system." The Karroo system is clearly unconformable on the complex and on the Waterberg. The relation of the complex to the great sandstone-conglomerate member of the Waterberg is not so easily discerned. As shown in the following historical summary, opinions on this subject have varied fundamentally. Most writers have concluded that the Waterberg system is older than the norite and granite of the complex, and formed the roof of these intrusions. Yet certain facts of the field could not be readily reconciled with that view. Accordingly, a revision of the field evidence which seemed to indicate intrusion of the Waterberg sandstone by the granite appeared necessary, and this problem was assigned to the writers of the present article.

Their conclusion is that the Waterberg sandstone-conglomerate is definitely unconformable on the Red Granite, and still younger than the norite, granophyre, and felsite of the Bushveld complex. These facts necessitate a redefinition of the Waterberg system, from which the Rooiberg quartzites and analogous strata must be separated, because older than the unconformably overlying Waterberg.

At two localities, and at two only, is an intrusive relation of the coarse granite to the Waterberg supposed to have been proved—at Balmoral and at Gatkop in the western part of the Hoekbergen. The new field evidence, showing the true relation to be one of unconformity, will be presented, after a preliminary glance at the history of opinion as to the nature and age of the igneous complex.

HISTORICAL SUMMARY OF OPINION

To facilitate an understanding of the development of knowledge regarding the complex, the accompanying table of formations in the Transvaal is presented.

Before the inauguration of the Geological Survey of the Transvaal Republic, Cohen, Henderson, and others had made petrographical studies of the coarse granite, norite, and associated

pyroxenite, but the individuality of the Bushveld complex had not been made clear. A first, necessary step was taken by Molengraaff when he showed that the coarse Bushveld granite belongs to a

TABLE I*

Formations		Age
SUPERFICIAL DEPOSITS		
	(*Unconformity*)	
KARROO SYSTEM		
Upper Karroo...	Bushveld Amygdaloid	?
	Bushveld or Buiskop sandstone	Triassic
Middle Karroo...	Highveld or Beaufort series, with coal-measures	Permian
Lower Karroo...	Ecca series	Permian
	Dwyka conglomerate (tillite)	Carboniferous
	(*Unconformity*)	
WATERBERG SYSTEM		?
	(*Unconformity*)	
BUSHVELD IGNEOUS COMPLEX		?
TRANSVAAL SYSTEM		Probably pre-Devonian
Pretoria series		
Magaliesberg quartzite		
Shales		
Daspoort quartzite		
Shales		
Timeball Hill quartzite		
Shales, sandstone, and conglomerate		
Dolomite series		
Black Reef series		
	(*Unconformity*)	
VENTERSDORP OR VAAL RIVER SYSTEM		?
	(*Unconformity*)	
WITWATERSRAND SYSTEM		?
	(*Unconformity*)	
SWAZILAND SYSTEM, INTRUDED BY "OLD GRANITE"		?

* Many minor eruptive bodies are not entered in the table. These include: certain extrusives interbedded in the Transvaal system; many dikes and sheets, including those cutting the Upper Waterberg sediments; and the alkaline masses, typified by the Pilandsberg, Leeuwfontein, and other intrusives.

formation very different from the much more widely extended "Old Granite." The former was shown to be younger than the Transvaal system; the latter, much older. In his 1898 *Report*, Molengraaff described the basic rocks (norite and pyroxenite)

and acid rocks (red granite and granophyre) of the Bushveld area as belonging to one and the same, igneous complex, the pyroxenite and norite representing the lower differentiates of a huge flow of magma, of which felsite and felsite-porphyry represent the upper differentiates.[1]

The history of the complex was given as follows:

> After the deposition of the Magaliesberg beds, the upper division of the Pretoria series . . . . there followed a period of volcanic activity on a very large scale. The limited geological data from this district, with which up to the present we are acquainted, appear to justify the hypothesis that the eruption set in with the extrusion of loose volcanic material, as tuffs and scoriae; thereupon followed lava streams of very diverging chemical composition, grading from very basic rocks belonging to the olivine-diabase and pyroxenite groups to the very acid, as felsite porphyry and quartz porphyry, the latter predominating. Contemporaneously with this, the rocks of the Cape (now Transvaal) Formation were greatly disturbed, and the fissures formed were injected with similar eruptive material. The innumerable dikes of eruptive rocks of very varying composition which are found in the uppermost layers of the Pretoria series to the north of the Magaliesberg afford evidence of this. The bed of the Pienaars River, on the farms Baviaanspoort 470, Leeuwfontein 320, Zeekoegat 287, and Roodeplaat 314, offer excellent opportunities for the study of the earlier results of the above-mentioned igneous activity. Then followed the outpouring of a sheet of lava of granitic composition, of enormous extent and thickness, which in its central and lower portions consolidated to a "granite" with micropegmatitic structure, whereas the portion nearer the surface furnished rocks belonging to the quartz porphyry, felsite, and felsite-porphyry groups. The facts, so far as known, lead us to suppose that at or near the bottom of this magma, the basic constituents (in which the Red Granite itself is very poor) accumulated, forming granular crystalline rocks, gabbro, diallage norite, etc., from which, finally, the ultrabasic materials separated out in turn as chrome-iron ore and magnetite respectively. Possibly the period of volcanic activity closed with the ejection of loose volcanic material, which subsequently was removed to a great extent by erosion, and to which probably belongs the felsite-porphyry tuff found north of Middelburg. It is not unlikely that the well-known Salt Pan to the north of Pretoria, with its remarkable crater-like form, indicates one of the eruptive centers of the period referred to. It is not certain yet whether the Bushveld amygdaloid which

[1] G. A. F. Molengraaff, "De volgorde der geol. formaties in de Zuid-Afrikaansche Republiek," *Rapport van den Staats-Geoloog over het jaar 1898* (Pretoria, 1899), pp. 3–7; an English translation of this *Report* was published at Pretoria in the year 1902. It contains many errors which are corrected in the quotations here given in the text.

almost everywhere on the Springbok Flats composes the subsoil, is genetically connected with this period of volcanic activity; possibly it represents the final outflow.

Molengraaff proposed the name "Waterberg sandstone" for a series of sandstones resting on the felsite and Red Granite of the Waterberg district, and stated that an appreciable time must have elapsed between the consolidation of the Red Granite and the deposition of the sandstone. The conglomerate at the base of the sandstone series was described in some detail, and mention made of pebbles of felsite porphyry contained in this basalt conglomerate.

The Red Granite as well as the Waterberg sandstone were preliminarily incorporated in the Cape (now Transvaal) system, with the remark that "not unlikely, further research would show that the Waterberg Sandstone Formation does not belong to the Cape System, but that it occupies a distinctive position between it and the Karroo System."

Difficulty was found in explaining the occurrence of certain dikes of felsite porphyry and felsite-porphyry breccia and of others composed of quartz and hematite, cutting across the Waterberg sandstone. The *Report* states:

> Between the solidification of the Red Granite and the deposition of the Waterberg conglomerates and sandstones, there must have elapsed a period of erosion and denudation. Thus it is very remarkable that dikes of felsite porphyry and felsite-porphyry breccia are found in this sandstone, but the data collected up to the present do not lend themselves to a satisfactory elucidation of this. To enable us to explain this, we must assume that the volcanic agencies which brought the Red Granite and felsite porphyry to the surface, renewed their activity after the deposition of the Waterberg sandstone.[1]

Clearly the Bushveld complex was then considered by the author of the *Report* to be the result of extrusions, and no mention was then made of a possible laccolithic origin.

In a revised German translation of the 1898 *Report* ([Pretoria, 1900], p. 17) it was suggested that the Red Granite with its associated igneous rocks might represent a much denuded intrusion and not a gigantic extrusive sheet. In the year 1901 Molengraaff again

[1] G. A. F. Molengraaff, "Schets van de geol. gesteldheid van het district Waterberg," *op. cit.* (with geol. map), pp. 22 and 26.

outlined the probable history of the intrusions.[1] He tentatively assumed that the Waterberg sandstone had originally been laid down conformably on the Pretoria series, and that later the rocks of the Bushveld complex were intruded in the form of a huge laccolith, between these two groups of strata. It was, however, admitted that the true position of the Waterberg was uncertain and that many apparently well-established facts pointed to an unconformable relation between the Waterberg and the Transvaal systems.

In the year 1902 the same author suggested the possibility of more than one laccolithic intrusion having taken place to form the whole complex.[2]

At various places the unconformity between the Waterberg and Transvaal systems was demonstrated by Dorffel (1903) and Mellor (1904).[3]

In his 1903 *Report* Mellor described observations which seemed to him to show the Red Granite west of Balmoral to be an interformational laccolith, injected into the contact of the Waterberg and Transvaal systems.

The following year Jorissen gave fresh evidence of the unconformity between the Waterberg system and the Magaliesberg quartzite of the Transvaal system, deriving his facts from the country west of Warmbaths.[4] For the present problem interest centers in his description and naming of the Elandsberg quartzites.

[1] G. A. F. Molengraaff, "Géologie de la République S. Africaine," *Bull. soc. géol. France*, 4, Vol. 1 (1901), p. 13; a revised edition in English, *The Geology of the Transvaal*, by G. A. F. Molengraaff and J. H. Ronaldson, was published in book form at Edinburgh, 1904.

[2] G. A. F. Molengraaff, "Vice-President's Address," *Trans. Geol. Soc. South Africa*, Vol. V (1902), p. 72.

[3] D. Dorffel, "The Balmoral Cobalt Lodes," *Trans. Geol. Soc. South Africa*, Vol. VI (1904), p. 94; E. T. Mellor, "Report on Portions of the Pretoria and Middelburg Districts," *Ann. Rept. Geol. Survey, South Africa, for 1903*, pp. 7–27, and "The Waterberg Sandstone Formation," *Trans. Geol. Soc. South Africa*, Vol. VII (1905), pp. 39–50. It may be noted that H. S. Harger (*Trans. Geol. Soc. South Africa*, Vol III [1898], p. 107) had already recognized the unconformable relation of the "red sandstone" (Waterberg sandstone) to both the underlying Transvaal system and the overlying Karroo.

[4] E. Jorissen, "On the Occurrence of the Dolomite and Chert Series in the Northeast Part of the Rustenburg District," *Trans. Geol. Soc. South Africa*, Vol. VII (1904), p. 30.

These rest on the Red Granite, which has metamorphosed the quartzites, with the generation of new feldspar (feldspathization) and small radial aggregates of specular iron and epidote. Pegmatites, consisting of red feldspar and quartz, cut across the quartzite. Indorsing Molengraaff's idea that the Bushveld complex was injected as an enormous laccolith in the upper beds of the Pretoria series, Jorissen suggested, as a working hypothesis, that the Elandsberg quartzites belong to the Pretoria series, and thus represent the roof of the laccolith, the Waterberg sandstone being deposited later unconformably on these quartzites and on the Red Granite.

In 1904 Hall, working in the Bushveld tin-fields, proved that the Red Granite underlies and intrudes the felsite, but also mentions a clear instance of a transition, complete within 200 yards, between Red Granite and felsite. The locality is near Hamanskraal station.[1] He is of opinion that the felsite was intruded, sheetlike, in the Waterberg sandstone, and that later both of these formations were intruded by the Red Granite. Hall found the granite to be marginally modified, so as closely to resemble the felsite.

During the same season Kynaston and Mellor were making a reconnaissance of the southeastern part of the Waterberg district. They found the felsites north of Hartingsburg to resemble flows rather than intrusive rocks, and to inclose interbedded dark shales. This group is directly overlain by conglomerates of the Waterberg system; some pebbles of the conglomerate are composed of felsite. Near Nylstroom veins of fine-grained granite traverse the felsites. The observations suggest an intrusive relation of the Red Granite to the felsite.[2] Southwest of Moorddrift station Mellor found the Red Granite, near the junction with the overlying Waterberg sandstone, to become finer-grained, passing into a compact felsitic type. This felsitic character is persistent throughout the whole visible line of junction. These facts and the absence of granite

[1] A. L. Hall, "Geological Survey of the Northeast Portions of the Pretoria District," *Ann. Rept. Geol. Survey, Transvaal, for 1904* (Pretoria, 1905), pp. 37–44; "The Bushveld Tin Fields," *Trans. Geol. Soc. South Africa*, Vol. VIII (1906), pp. 47–55. See Plate XXII, Fig. 1, of the *Annual Report.*

[2] H. Kynaston and E. T. Mellor, "A Traverse from Pretoria to Pietersburg," *Ann. Rept. Geol. Survey, Transvaal, for 1904*, pp. 11–25.

pebbles in the Waterberg conglomerates led Mellor to believe that the Red Granite is intrusive into the Waterberg sediments.

The interesting area of Rhenosterkop in the Middelburg district, where earth movements have tilted the Waterberg strata and the underlying granite, gave Mellor the opportunity of describing a complete section through the lower part of the Waterberg system.[1] He distinguished, in descending order:

TABLE II

Sequence of Beds in the Waterberg Formation at Rhenosterkop, 1904	Approximate Thickness in Feet
WATERBERG SYSTEM	
Red and purple, thick-bedded sandstones and grits, with thin conglomerates	2,000
Coarse conglomerates, passing upward into small-pebble conglomerates and sandstones	400
Volcanic agglomerate with abundant bowlders and fragments of banded felsites	350
Hard, black, and purplish shales and flags, passing upward into conglomerates	400
Total	3,150
FELSITE	
GRANITE	

Mellor states that the felsites are in part apparently younger than the lowest Waterberg shales, but are older than the purple and brown conglomerates, which succeed the red agglomerate and pass upward into the thick upper sandstones of the Waterberg system. The occurrence of the red volcanic agglomerate shows that the period represented by the lower part of the Waterberg was marked by vigorous volcanic activity. Mellor states that he failed to find any evidence of a sedimentary junction between the Waterberg sandstone and the Red Granite, and that the observed relations point to intrusion of the Waterberg by the granite.

As a result of studies in the northern Transvaal and in the Rustenburg district, Holmes concluded that the Waterberg sandstone lies unconformably on all other bedrock formations in the

[1] E. T. Mellor, "Geology of the Neighbourhood of Rhenosterkop," *Ann. Rept. Geol. Survey, Transvaal, for 1904* (Pretoria, 1905), pp. 45–55.

Transvaal, except the Karroo beds.[1] In the Zoutpansbergen, quite outside the Bushveld, it rests unconformably on the Old Granite and associated schists. The unconformity with the Red Granite is sufficiently demonstrated by the presence of pebbles of this granite in the Waterberg conglomerate, and also by the fact that in the northern part of the Transvaal, the Waterberg lies in a practically horizontal position upon the Red Granite, as well as on the Old Granite and gneiss. He also mentions a few localities where there is a gradual transition between coarse Red Granite and quartz-felsite and microgranite. Holmes considers the Waterberg sandstone to be a formation deposited along a receding shore line.

In the year 1906 the Geological Survey of the Transvaal published a table of formations, in which for the first time a division of the Waterberg system into two groups is officially adopted; namely, an upper group, comprising the sandstone and conglomerates, and a lower group comprising the felsitic lavas and agglomerates and shales.[2]

The following year knowledge about the character and stratigraphy of the Waterberg system was greatly increased again by Mellor, as a result of his survey of the central part of the Middelburg district.[3] In descending order he subdivided the system as follows:

TABLE III

Classification of the Waterberg System, 1906	Approximate Thickness in Feet
WATERBERG SYSTEM	
Upper division:	
Sandstone and quartzite series: sandstones, quartzites, grits, and conglomerates	5,000
Shale and sandstone series: shales and soft sandstones (with conglomerates at the base)	2,000
Lower division:	
Volcanic series: lavas, tuffs, breccias, and agglomerates, with interbedded shales and sandstones	8,000
Total	15,000

[1] G. G. Holmes, "Notes on the Geology of the Northern Transvaal," *Geol. Trans. Soc. South Africa*, Vol. VII (1904), pp. 51–56.

[2] H. Kynaston, *Director's Report for 1905* (Pretoria, 1906), p. 16.

[3] E. T. Mellor, *Ann. Rept. Geol. Survey, Transvaal, for 1906*, p. 55; *Trans. Geol. Soc. South Africa*, Vol. X (1907), p. 44; "Explanation Sheet 3 (Middelburg)," *Geol. Survey*, 1907.

Volcanic action of the Lower Waterberg time must have represented one of the most important phases of the geological history of the Transvaal.[1] In the paper just cited, Mellor concluded that the new evidence fully justifies Molengraaff's conception of the Red Granite as a gigantic laccolith, injected below the Waterberg, though the roof of the laccolith must be placed at a very much lower horizon than appeared possible from the evidence formerly available. Mellor referred the intrusion of the Bushveld complex to a period subsequent to the deposition of the entire upper sedimentary division of the Waterberg system. As to the felsitic rocks, Mellor points out that some of them doubtless represent fine-grained varieties of the Red Granite, but that in many cases they belong to the acid flows which characterize the lower part of the Waterberg.

In 1906 Humphrey found felsite forming an intrusive sheet at a high horizon of the Pretoria series. He also described the Rooiberg quartzites, which weather with a pitted surface, owing to a high content of feldspar.[2] These rocks are the same as the Elandsberg quartzite of Jorissen.

Kynaston, in 1907, stated that the Red Granite and the great norite both belong to the same general period of intrusion, the former being slightly the younger and intrusive into the Waterberg system. The eruption of the Bushveld complex was considered by him as probably referable to the period that intervened between the deposition of the Waterberg and the beginning of Karroo sedimentation.[3]

In connection with the tin deposits of the Rooiberg-Elandsberg area, Recknagel (1908) studied the feldspathic Elandsberg or Rooiberg quartzite, with its intercalated shales and sheets of diabase, finding that these sediments were altered by intrusive Red Granite. The quartzite is overlain by felsite and dikes of felsite cut through it. Recknagel gives a sketch of the magnificent intrusive contact

[1] H. Kynaston, "Director's Report," *Geol. Survey, Transvaal, for 1906* (Pretoria, 1907), p. 5.

[2] W. A. Humphrey, "On a Portion of the Bushveld Lying South of the Rooiberg and East of the Crocodile River," *Ann. Rept. Geol. Survey, Transvaal, for 1906* (Pretoria, 1907), p. 109.

[3] H. Kynaston, "Geology of the Country Surrounding Pretoria," *Explanation of Sheet 1, Geol. Survey*, Pretoria, 1907.

between the Red Granite and the Rooiberg quartzite on Hartebeestpoort. Although a dike of granophyre is described as breaking through the felsite on the farm Welgevonden, the relationship between the Red Granite and the felsite is considered to be obscure.[1]

Mellor (1908) surveyed a considerable part of the Waterberg district, and came to conclusions which may be summarized as follows: The felsites with the associated shales form the Lower Waterberg. The Red Granite is everywhere intrusive into the felsite, though near the contact the granite often shows a finer grain and the felsite a coarser grain—facts which tend to obscure the actual relations. The upper Waterberg, with well-marked conglomerates at its base, rests with a slight unconformity on the rocks of the lower division of the system.

Mellor believed that the occurrence of pebbles and tourmalinized rocks in the basal conglomerate show at least some of the granitic intrusions, including that which brought about the mineralization of the lower division, to have been earlier than the Upper Waterberg. On the other hand, he thought he had good evidence of intrusion of the Upper Waterberg at Gatkop by the Red Granite, showing that intrusions of the Red Granite also occurred after the deposition of the upper division of the Waterberg.[2]

The same conclusion is restated in a paper dealing with the margin of the Bushveld, at and eastward from Gatkop. In addition he describes a remarkable disturbance of post-Waterberg age, whereby the lower beds of the Upper Waterberg have been tilted up at right angles. Near the summit of Gatkop a portion of the Transvaal series was thrust over the Red Granite and the Waterberg sediments. Thus Mellor confirmed the existence of powerful, though local, diastrophism in post-Waterberg time—the discovery he had first made at Rhenosterkop.[3]

In the same volume Humphrey advocated the separation of the Elandsberg quartzite (Jorissen) or Rooiberg quartzite (Recknagel)

[1] R. Recknagel, "Some Mineral Deposits in the Rooiberg District," *Trans. Geol. Soc. South Africa*, Vol. XI (1909), p. 83.

[2] E. T. Mellor, "On a Portion of the Waterberg District West of Potgietersrust," *Ann. Rept. Geol. Survey, Transvaal, for 1908* (Pretoria, 1909), p. 27.

[3] E. T. Mellor, "Geology of the Hoekbergen in the Waterberg District," *ibid.*, p. 54.

from the Pretoria series to which it was supposed to belong, and its inclusion in the Lower Waterberg as a separate rock-group below the volcanic group. For this lowest subdivision of the Waterberg system he proposed, for the purpose of official mapping, the name "Rooiberg series."[1]

Writing on the Waterberg tin-fields, Kynaston and Mellor indorse Humphrey's views about the Rooiberg series, and again emphasize the belief that the Red Granite was erupted both before and after the deposition of the Waterberg system.[2]

In his anniversary address to the Geological Society of South Africa, Kynaston (1909) gave a clear account of the ideas then held as to the mode of intrusion of the Bushveld complex and as to its relation to the overlying sedimentary formations. Because this statement has expressed the official view of the Geological Survey ever since, it is worth while to quote it in full:

> With regard to the general mode of intrusion, we may conceive that this commenced by an upward movement of the magma, which gradually invaded and broke through the Transvaal System, detaching and engulfing large masses of it, then spreading itself out, after the manner of a huge sheet, between the Pretoria Series and the unconformably overlying Waterberg System. This breaking up of the Transvaal System over the central portion of the area is well shown by the numerous detached masses of the Pretoria Series, Dolomite, etc., so frequently found now completely surrounded by the plutonic masses. These may be regarded as representing the surviving remnants of that portion of the sedimentary cover which was broken up. Part of this sank, while other parts remained supported as the magma beneath them became more and more viscid. To what extent, however, such a process has been operative must necessarily remain somewhat obscure, though I think there is good evidence that its effects have been very considerable. Also, as to whether there has been actual digestion of sedimentary rocks on the part of the magma is another question by no means easy to decide.
>
> If we come now to enquire more particularly into the relation of the Red Granite to the Waterberg System, several additional puzzles are met with, requiring further systematic work before they can be completely disentangled. The Volcanic Series, with its associated sediments, forming the lower portion of the System, can be shown in many places to have been invaded by the

[1] W. A. Humphrey, "On a Portion of the Bushveld Bordering the Crocodile River and Including the Rooiberg Tin Field," *ibid.*, p. 105.

[2] H. Kynaston and E. T. Mellor, "Geology of the Waterberg Tinfields, Memoir No. 4," *ibid.*, 1909.

granite. With regard to the Upper Series of sandstones and conglomerates, however, the evidence is by no means so clear. In fact, the question as to whether the Red Granite is earlier or later in age than the Upper Waterberg Beds has for some time been a subject of some discussion. Certain evidence, however, met with during the recent work of the Geological Survey in the Waterberg District, will probably throw a good deal of further light upon the subject. In several localities boulders of granite have been found in the conglomerates, lying at or near the base of the Waterberg Sandstones, these boulders being sometimes indistinguishable from characteristic varieties of the main mass of the Red Granite. Moreover, the local occurrence in the sandstones of fragments of tourmaline-bearing rocks, which has recently been referred to by Merensky, has been confirmed. Further, there is apparently a well-marked unconformity between the Upper Waterberg and the Lower or Volcanic Series, of which the Felsites here form the predominant feature, the beds of the Upper Waterberg showing a progressive overlap until they come to rest directly upon the Red Granite. Moreover, in the Magalakwin Valley, northwest of Potgietersrust, where this transgression takes place on to the granite, the basement beds of the Waterberg consist of a coarse red arkose, formed almost entirely of granitic material. There is thus strong evidence that the Upper Waterberg beds in the Waterberg District are of later age than the intrusion of the Red Granite, while the inclusion of boulders of tourmaline-rock in the sandstones would appear to show that they are also later than the mineralization of the granite.

On the other hand, it can be shown in certain localities that portions of the Red Granite are clearly intrusive into and therefore of later date than the Upper Waterberg. This has been proved by Mr. E. T. Mellor, at Balmoral, and additional evidence of such intrusion has recently been found by the same geologist near the boundary of the Waterberg and Rustenberg Districts.

The evidence, therefore, so far collected, is apparently contradictory, and at first sight somewhat perplexing, but I do not think it will be found difficult of explanation. Now, the general character and behaviour of the Red Granite seem to indicate that it was by no means likely that it was all intruded at the same time; indeed, it seems to me that one would scarcely be justified in assuming that such had been the case. It may well be that part of the Bushveld Complex was intruded into the Transvaal System and Lower Waterberg before the deposition of the Upper Waterberg sediments, and that these latter were laid down after this older portion of the Red Granite and the Volcanic Series had been partially exposed to denudation. Finally, later intrusions of Red Granite invaded the Upper Waterberg also. We may conclude, therefore, that the intrusive period of the Red Granite commenced before the deposition of the Upper Waterberg sandstones and conglomerates, and after the formation of the Volcanic Series, but was only finally concluded during the interval between Upper Waterberg and Lower Karroo times. Further evidence of the prolonged activity of the Bushveld magma is found in the intrusions in the

upper sandstones of diabase, felsite, etc.—the former sometimes showing transitions into acid granophyre.

In the central Transvaal we are also dealing with an ancient volcanic region, the strictly volcanic phase of which is represented by the Felsites and associated lavas and tuffs of the Lower Waterberg, and there is apparently a close genetic relation between these volcanic rocks and the more deep-seated granitic masses. May we not be therefore justified in concluding that the Bushveld Granite is simply the deep-seated or plutonic phase of the same magma from which these lavas were derived, so that we may have here first of all to take into account a volcanic or effusive phase in Lower Waterberg times, followed in due course, as in many other parts of the world, by a plutonic phase, during which part of the granitic magma was intruded into the overlying volcanic rocks? Finally the general igneous activity of the area was concluded by a later intrusive phase, after the deposition of the upper Waterberg Sandstones.

For convenience opinions now prevailing as to the relations of the Bushveld complex to the overlying formations may be summarized in somewhat different form.

1. After the Waterberg system and the rocks of the complex had undergone prolonged denudation, the Karroo system was unconformably deposited.

2. According to the Geological Survey of South Africa, the Waterberg system comprises the following formations:

UPPER DIVISION

Sandstone and quartzite series: sandstones, quartzites, grits, conglomerates, and locally some shales, with well-marked coarse conglomerates at the base of the series

Shales and sandstone series: shales, soft sandstones, and conglomerates. (This series is often wanting, e.g., at several localities in the Waterberg district)

(*Unconformity*)

LOWER DIVISION

Volcanic series: acid lava flows (felsites), tuffs, volcanic breccias and agglomerates, with interbedded shales and sandstones

Rooiberg series: feldspathized quartzites, with shales

3. The entire Waterberg system is held to be unconformable with the underlying Transvaal system.

4. The erosion unconformity between the upper and lower divisions of the Waterberg registers a time-interval long enough for the partial removal of roof rocks and chilled phases of the Red Granite.

5. In contrast with other subdivisions of the Waterberg system, the Rooiberg series cover, in all, but a limited tract of ground. These rocks have been mapped in the Waterberg, Rustenburg, Pretoria, and Stavoren districts, and are found to cover a total area of only about 250 square miles (640 sq. km.). The Rooiberg never crops out except in the heart of the Bushveld complex—a relation not easily understood if this rock-group represents an independent formation. It may be added that members of the Geological Survey have noted some striking resemblances between the Rooiberg quartzites and those of the Pretoria series.

6. The Red Granite intrudes the Lower Waterberg. This relation with the felsites is not seldom obscured by the fact that at the mutual contact the felsite shows an unusually coarse grain and the granite shows unusually fine grain.

7. After the erosion interval registered between the Upper and Lower Waterberg divisions, renewed eruption of the Red Granite magma took place, and this magma cut rocks of both divisions.

8. Sheets and dikes of diabase, felsite, etc., injected into the strata of the Upper Waterberg, also give evidence of this later invasion of the Bushveld magma.

9. The felsites and associated lavas and tuffs of the Lower Waterberg represent the volcanic phase of the magma whose plutonic phase is represented in the Red Granite, which is intrusive into the volcanics.

10. Locally, as in the Hoekbergen (Gatkop) and at Rhenosterkop, overthrusting or overtilting has caused the Red Granite to lie under the older formations of the Transvaal system.

11. As shown by Kynaston and Hall, the great noritic member of the Bushveld complex is distinctly older than the coarse Red ("ball") Granite, which has diked the norite and even made plutonic breccias with it. On the other hand, a similar relation between the norite and the very extensive, red granophyric granite and granophyre has not been demonstrated.

A CRITICAL QUESTION

Many of these conclusions are established beyond possibility of doubt, but some important points are worthy of discussion and

revision. Among them is the question whether the coarse Red Granite cuts the sandstone-conglomerate series now mapped as Upper Waterberg—the special subject of the following pages.

The answer to this particular question has been somewhat delayed by failure to note the true time-relations among the different members of the Bushveld complex, especially the felsite, granophyre, coarse granite, and norite. In some places, as west of the Zaaiplaats Tin Mine, the red granophyre is chilled against and cuts the felsite, which appears to be extrusive. Yet several observers have reported apparent transitions from felsite to granophyre, and there seems to be little doubt that these two formations are almost, if not quite, contemporaneous. In Sekukuniland at least, the granophyre is diked by apophyses from the great norite body, though the apophyses are generally quartzose and more silicious than norite. Hall has concluded that elsewhere the norite is transitional into granophyre, and here again all the facts so far ascertained seem to find best explanation on the hypothesis that norite and granophyre are nearly or quite contemporaneous eruptives. The order of solidification, beginning with the type crystallizing first, is felsite, granophyre, norite.

On the other hand, the coarse Red Granite or "ball" granite seems everywhere to be younger than the norite. Kynaston found the norite north of Potgietersrust to be shattered by, and inclosed in, typical coarse granite, the whole forming a plutonic breccia.[1] At Magnet Heights Hall found dikes of the coarse granite, clearly cutting the norite, and, east of Magnet Heights, Wright discovered a magnificent plutonic breccia of the granite and the older norite. Clearly a long time elasped between the crystallization of the granophyre-felsite magma and the intrusion of the magma forming the coarse Red Granite.

Much younger than the coarse Red Granite, and *a fortiori* younger than the great bodies of felsite and granophyre of the Bushveld complex, are the felsitic injections, cutting the sandstones of the Upper Waterberg. The Upper Waterberg red, salic intrusives have, in fact, not necessarily anything to do with the salic rocks of the Bushveld complex; still less can their discovery be cited as

[1] H. Kynaston, *Ann. Rept. Geol. Survey, Transvaal, for 1908* (Pretoria, 1909), p. 18

proof of an intrusive relationship between the coarse Red Granite and the upper division of the Waterberg. The assumption that *all* the red felsites of the Transvaal, as well as the coarse Red Granite and the norite, belong to a single petrogenic cycle or eruptive period is opposed by the fact that pebbles of the older felsites, of the granophyre, and of the coarse Red Granite are inclosed in the basal conglomerates of the Upper Waterberg system. The implied erosion-unconformity between the Upper Waterberg and the felsite of the Bushveld complex was deduced by Molengraaff as early as 1898, and has been amply proved during the succeeding years. Moreover, with the same criterion the unconformity of the Upper Waterberg with the granophyre and coarse Red Granite has been demonstrated.

The stratigraphic situation became complicated when, at Balmoral and at Gatkop, evidence seemed to point to an intrusive relationship between the Upper Waterberg sandstone and at least some bodies of the coarse Red Granite. That the evidence at each of these localities shows, on the contrary, decided unconformity is the main thesis of this paper.

It appears equally clear that the same erosion interval separates the deposition of the Rooiberg series and the Sterk River shales, and similar sedimentary lenses interbedded or inclosed in the older felsites, from the epoch when the lowest bed of the Upper Waterberg was laid down. In the writers' opinion the Rooiberg series of rocks probably represents metamorphosed members of the Transvaal system. They believe that the Waterberg system should include only those sediments which have been mapped by the Geological Survey as "Upper Waterberg." Throughout this paper the name "Upper Waterberg" is used with the meaning given to it in coloring the official maps of the Survey.

With these preliminary remarks in mind, the significance of the observations now to be presented will be better appreciated.

RELATION OF THE COARSE RED GRANITE TO THE WATERBERG SYSTEM AT BALMORAL

In the *Annual Report of the Geological Survey of the Transvaal for 1903*, Mellor published the first detailed evidence which suggested to him an intrusive relation between the coarse Bushveld

granite and the great sandstone-conglomerate division of the Waterberg. The critical sections were found close to Balmoral station, on the Delagoa Bay railway, about 40 miles east of Pretoria. The Middelburg map-sheet shows the outcrop of the Balmoral granite to cover about 3 square miles (8 sq. km.).

As Mellor states: "There can be little doubt that the Balmoral intrusion is connected in origin with the main mass of the Red Granite farther north" (p. 13 of his *Report*). He concluded that the Balmoral granite is a laccolith injected into the Waterberg sediments near the base of that series. The evidence for intrusion in summarized in these words:

> The upper surface of the granite intrusion, while following in general the bedding of the overlying Waterberg rocks, frequently breaks across from one bed to another of different character, so that it immediately underlies in one place shales, in another breccia, and again in others sandstones, as shown in Fig. 4, Plate XVII, which represents an ideal section of the face of the ridge, taken at right angles to the sections in Figs. 1, 2, and 3.
>
> The shales at the east end of the ridge have suffered most disturbance and alteration from the intrusion of the granite. Many huge shale fragments are included in the upper portion of the granite mass. The shales are everywhere baked, altered, brecciated and frequently penetrated by intrusive veins of granitic material (see Plate V, Fig. 1).
>
> The breccias and conglomerates have also been much broken up, and in some places large masses of typical breccia and isolated quartzite fragments and pebbles are found completely embedded in the upper portion of the granite. Hand-specimens can be frequently obtained, showing the contact of the igneous and sedimentary rocks. On the other hand, the sandstones of the sedimentary series appear to have yielded more uniformly to the intrusion of the granite, which follows their bedding for considerable distances.
>
> Near the contact with the sedimentary series, the upper portion of the granite has taken on a remarkably well-developed platy or pseudo-stratified structure, weathering in mural fashion and giving rise over long distances to a well marked "kranz" or escarpment. At a little distance, this kranz has every appearance of consisting of a thick-bedded stratified rock. This structure of the upper portion of the granite mass is well seen in the photograph (Plate IV, Fig. 2).
>
> Coincident with the transition from the massive structure of the deeper portions of the laccolite to the platy structure of its upper portions is a gradual change petrologically from the typical coarsely crystalline granite to a rock consisting mainly of abundant quartz grains in a close red felsitic ground mass, and containing very little ferromagnesian material.

Many interesting variations of the granite, which would well repay detailed study, are to be found along the region of contact with the sedimentary formation [pp. 13–14].

The contacts of the granite with the shales and sandstones of the Waterberg formation are frequently so definite as to be clearly seen within the limits of a microscope slide. The relation of the granite to the rocks of the Pretoria series is not so clear, but at Balmoral the granite intrusion appears to have followed pretty closely the unconformable junction between the Pretoria and Waterberg series [p. 26].

Mellor's main conclusion has ever since been important in the history of opinion as to the stratigraphy of the Transvaal and as to the *mise en place* of the Bushveld complex. Since the latter problem was one of the chief incentives to the organization of the Harvard-Carnegie expedition, a new study of the Balmoral sections seemed advisable. Accordingly, one of the present writers (Daly), in company with Dr. Wright, visited Balmoral, in March, 1922. During the following June, a second visit was made by Daly, accompanied by Dr. Palache, who, like Dr. Wright, added materially to the field data. These, together with subsequent microscopic studies, appear to permit of no doubt that the Waterberg sediments at Balmoral are unconformable upon the coarse Red Granite. The following summary of facts relates principally to observations made at Mellor's sections at Southwest Hill, about 1 mile southwest of Balmoral railway station. Similar data and conclusions were obtained at another well-exposed contact of the Red Granite and the Upper Waterberg, at the highway about 2.5 miles west of the station.[1] No other contacts have been found in the Balmoral district.

Through a thickness of from 10 to 30 meters, there is a gradual transition from the relatively fresh coarse Red Granite to gray or yellowish arkose, which makes an abrupt contact with the purplish Waterberg sandstones. The arkose has been statically metamorphosed, with the development of abundant quartz and sericite in place of the original feldspar grains. The alteration is in part responsible for the rude layering of the "granite" at and near the contact, a structure described in the foregoing quotation from Mellor.

[1] This contact is not shown on Mellor's original map nor on the Middelburg map-sheet of the Geological Survey.

Neither the writer (Daly) nor his colleagues could find any evidence of contact chilling of the granite or any signs of contact metamorphism in the Waterberg sediments overlying the granite. The sandstones and more argillaceous beds are there identical in habit with specimens collected at points several kilometers from the contact and clearly hundreds of meters from any possible igneous contact. In fact, neither the degree of induration nor the mineralogy of the shales and sandstones at the Balmoral contacts differ essentially from standard specimens of the Waterberg wherever developed in the Transvaal.

Prolonged search was made for possible apophyses of the granite. One tonguelike offshoot of the arkosic material, 15 to 20 centimeters in exposed width and sharply cross-cutting the sandstone for at least 20 centimeters, was discovered by Dr. Palache, but he agrees that this unique case probably represents an injection of arkosic sand—a "sandstone dike"—rather than a true igneous tongue. Possibly it was this same offshoot which Mellor described as an apophysis. No other case, even suggesting an igneous tongue, was found.

The large angular slabs of standstone, figured by Mellor as xenoliths in the granite, seem rather to be explained as blocks faulted down a few decimeters or meters into the arkosic shell. Corresponding fault-faces, distinctly slickened, were discovered.[1] In addition, some surface slumping appears to have produced the appearance of the inclosure of sandstone blocks in the arkosic granite. The arkosic surface on which the bedded sediments were laid was to some degree irregular; in a few cases erosion has given the sandy lenses deposited in the depressions the deceitful look of being inclosed in the "granite." In any case no evidence of true igneous, xenolithic inclosure could be discovered.

No undoubted pebbles of the Red Granite were seen in the local Waterberg conglomerate. On the other hand, the quartz and feldspar grains of the sandstone have sizes and optical properties identical with those of the same mineral species in the granite. Small pebbles and grains of typical Bushveld granophyre were found in the sandstone close to the contact with the arkose.

[1] The granite-Waterberg contact is broken by faults of greater throw, shown on Mellor's map, Plate XXII, of the *Annual Report of the Geological Survey for 1903.*

The cumulative evidence thus briefly described seems clear enough to establish the unconformity between the Balmoral granite and the overlying Waterberg sediments. The time-interval between the intrusion and the deposition of the lowest stratum was considerable. The coarseness of the granite, everywhere, shows that the thickness of its roof was notable; the necessary erosion antecedent to the local Waterberg sedimentation must have taken much time. The injected roof of the granite was doubtless in part composed of the hard Transvaal quartzites, remnants of which may be seen in contact with the Balmoral granite.

It was evidently desirable to examine Gatkop, the other locality where typical Waterberg sediments have been supposed to be intruded by the coarse Bushveld granite. Accordingly, in July, 1922, one of the writers (Molengraaff), accompanied and aided by Dr. A. W. Rogers, director of the Geological Survey of South Africa, studied this section.

RELATION OF THE RED GRANITE TO THE WATERBERG SYSTEM AT GATKOP

In the *Annual Report of the Geological Survey of the Transvaal for 1908* Mellor published a "Memoir" on the interesting disturbances found at and near Gatkop on the farm Donkerpoort No. 945 in the northeastern corner of the Rustenburg district, and on the relations between the Red Granite, the Felsites, and the Waterberg sandstone series there. Figure 2, taken from Mellor's "Memoir" (his Fig. 7), will help the reader to understand his explanation of the geology of this area.[1]

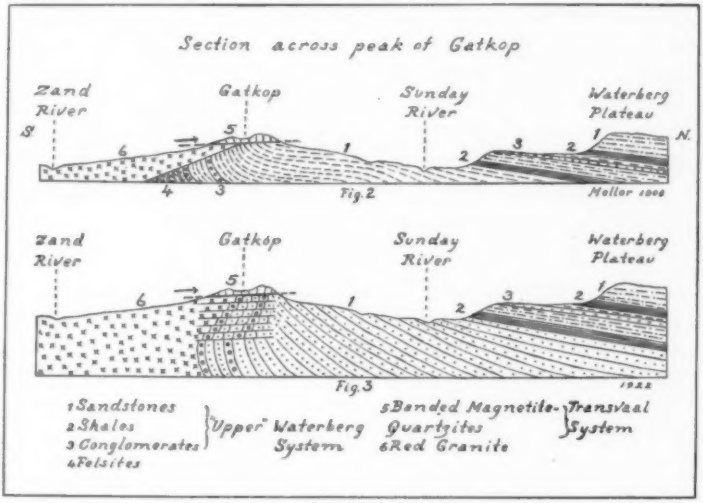
The exceptionally fine section in this figure can be well studied in a gully above the poort on Donkerpoort giving access to the steep and deeply dissected eastern slopes of the Gatkop peak, which attains an elevation of 2,800 feet above the base of the mountain. Mellor reads the section as follows (p. 55):

> It will be seen from the section given that the Waterberg Beds which run into the base of Gatkop have suffered a considerable degree of folding, resulting in very high dips at the base of the sandstones gradually diminishing in the upper portion of the series, ... structure very commonly met with at the margin

[1] E. T. Mellor, "Geology of the Hoekbergen," *Ann. Rept. Geol. Survey, Transvaal, for 1908* (Pretoria, 1909), pp. 54–60.

of the Waterberg System. The basal conglomerate and the beds immediately succeeding it are here in fact overtilted in places to an angle of 70 degrees, a condition well seen about the foot of the main gully which descends the eastern face and joins the spruit at the poort. This gully offers one of the best traverses of the eastern end of the mountain. The sharp flexure in the sandstones resulting in some places in a number of small faults, accompanied by numerous small quartz veins, is well exposed in the spur which forms the northern side of the gully referred to.

Towards the top of the mountain the upturned edges of the Waterberg strata are covered by the mass of banded magnetite-quartzites which form its crest. Beneath the northern peak at an elevation of about 2,000 feet above the



FIGS. 2 AND 3

base, the banded quartzites of the Transvaal System rest directly upon massive beds of Waterberg grits, while below the south peak the rocks of the two systems are separated from one another by an intrusion of granite in the manner shown in the section in Fig. 1. The eastern end of Gatkop thus shows with exceptional clearness a strongly marked overthrust fault, along which the banded quartzites of the Pretoria Series have overridden the edges of the Waterberg strata. Along the fault-plane has been intruded a mass of Red Granite which now partially separates the rocks of the two systems. This granite mass forms the whole of the spurs which descend from just below the southern peak to the poort, and is continued with the broad stretch of granite which occupies

the valley to the south-east of the mountain on Donkerpoort No. 945 and Zandspruit No. 953. The crest of the mountain is everywhere of banded quartzites. In the gully descending to the poort, already alluded to, the contact of the granite with the Waterberg conglomerates and sandstones is well exposed and can be closely followed almost from bottom to top, and single hand-specimens which include both igneous and sedimentary rocks can be obtained. The well marked marginal phenomena shown by the granite leave no doubt as to its intrusive relationship to the sediments, and its transgression from lower to higher horizons of the nearly vertical beds is clearly seen.

Thus according to Mellor the intrusion of the Red Granite is not only posterior to the deposition of the Waterberg sandstone but also posterior to the powerful orogenic pressure from the south which has upturned the southern edge of the Waterberg Plateau (Palala Plateau), overtilting the lowermost strata of the Waterberg sandstone series and thrusting a large block of banded magnetite-quartzites (belonging to the lowermost division of the Pretoria series or perhaps to the uppermost division of the Dolomite series) over the upturned edges of the layers of the Waterberg sandstone. The intruding granite has destroyed and probably assimilated a considerable portion of the lowermost strata of the Waterberg sandstone but, although being intruded, according to Mellor, along the fault (thrust)-plane, has not affected the rocks overlying this plane. An explanation of this contrast is not given, nor is it easy to imagine.

The study of this identical section in the gully on Donkerpoort by Rogers and Molengraaff in July, 1922, resulted in a different reading, which is illustrated in Figure 3. They limited their field observations to the relations between the Red Granite and the Waterberg sandstone series, entirely accepting Mellor's explanation of the occurrence of the banded magnetite-quartzites at the crest of Gatkop Mountain. Consequently, their section (Fig. 3) is identical with Mellor's (Fig. 2 of this paper), with the exception of the contact-zone between the granite and the Waterberg sandstone, which is sketched after their own observations.

The zone of contact which runs steeply upward along the eastern slope of Gatkop Mountain has been carefully studied, and no evidence whatever could be obtained of the supposed intrusive character of the granite. At Gatkop, and apparently over a great

distance from the mountain, the Red Granite is not typically developed, but has passed into a porphyritic variety closely allied to a quartz porphyry. This is probably a marginal modification of the granite near its contact with the felsite, which contact is exposed near by in the western portion of the Hoekbergen. Its color is dark purplish. This quartz-porphyritic variety of the granite is not restricted to, nor in any way genetically connected with, the contact on Gatkop.[1] In fact, no trace of a chill-phase in the granite along the contact could be found. Apophyses of the granite in the sandstone were not found, even after prolonged search.

Pebbles of a quartz-porphyritic granite identical with the rock *in situ* at the contact were found in the conglomerate near, and also some distance away from, the contact; nowhere, however, in abundance.

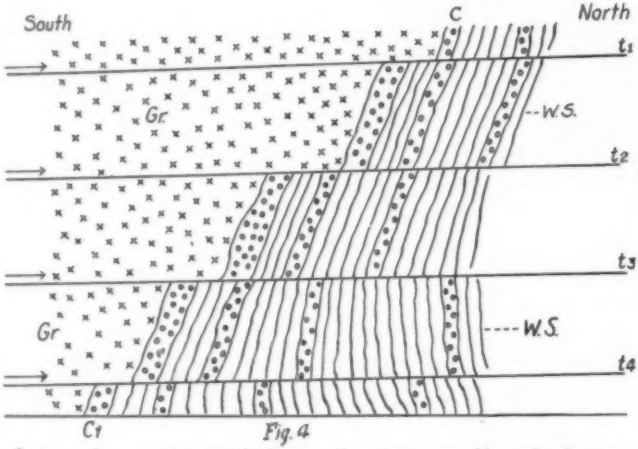
The Waterberg sandstone as far as examined is arkosic, and samples taken from near the contact must be termed highly arkosic. This character, however, on microscopical examination, proved of no help in the solution of the problem of the relation between the granite and the sandstone, because the numerous fragments of feldspar present in the sandstones are for the greater part made of plagioclase and microcline; they are most probably exotic, and derived from the disintegration of the much older, pre-Cambrian granite, which crops out at a considerable distance.

No contact-metamorphism is visible in the Waterberg sandstones and conglomerates; it is true that in places the sandstone near the contact was found to be harder than at some distance away, but this hardening appeared not to be caused by contact-metamorphism but by stronger cementation resulting from former circulation of solutions along the almost vertical plane of contact. At present, the granite and the Waterberg conglomerates and sandstones are well welded together in the plane of contact.

A succession of minor thrust-planes, running practically horizontal and parallel to the major thrust-plane near the summit

[1] Similar varieties of the Red Granite are recorded by Mellor (*Ann. Rept. Geol. Survey, Transvaal, for 1908*, p. 40) from near Hanglip on Klipspruit No. 267, and on Rooipoort No. 15 at the bank of the Groot Sterk River.

of Gatkop, is encountered in ascending the steep slope. These thrust-planes cut both through the granite and the sandstone (Fig. 4). The combined effect of the small thrusts is that the lowermost strata of the Waterberg sandstone series at Gatkop, seen from the distance, appear to be more overtilted than they really are; in reality between two of those thrust-planes the strata of the conglomerates and sandstones are found either to stand



Schematic representation of minor overthrust-planes t1--t4 on Gatkop C-C1. Sedimentary plane of contact between the Granite Gr and the Upper Waterberg System W.S., now overtilted.

FIG. 4

vertically or to be only slightly overtilted toward the north. Another effect is that in each slice a layer of conglomerate or sandstone abuts against granite, giving at first sight the erroneous impression of the granite's being intrusive in the sediments, and transgressing from lower to higher horizons in the sandstone. Wherever the slope is sufficiently clear from vegetation, it is easily seen that flat or low-dipping contact of the sediments and granite is located as one of these minor thrust-planes.

Owing to the great steepness of the slope, the line of contact could not be followed upward as far as the major thrust-plane, which underlies the banded magnetite-quartzites. If feasible, it certainly would be worth while to do so, because it may be expected that the system of parallel minor thrust-planes just described will, higher up at the sole of the major overthrust, develop into a typical imbricated structure.

Besides being faulted by the thrust-planes, both the granite and sediments show clearly the effects of shearing.

Apart from the faulting, the plane of contact between the granite and the sediments proved to be more or less uneven and undulating, the thickness and the grain of the individual layers of sandstone and conglomerate of the lowermost portion of the sedimentary formation showing marked variations over comparatively small distances; in short, the plane of contact has all the characteristics of an old surface composed of more or less decomposed quartz-porphyritic granite, on which the Waterberg sandstone series was laid down.

Taking into account the data given in Mellor's memoir, and in the Nylstroom sheet of the survey map, the study of this section justifies the following statement of the geological history of Gatkop and its immediate neighborhood:

After the Red Granite had been intruded into the quartzites and shales of the Rooiberg series and into the overlying felsites of the Gatkop area, a long erosion-interval occurred, resulting in the forming of an uneven, probably undulating surface, in which the Rooiberg quartzites, the Red Granite, and the felsites locally cropped out. On this uneven surface sedimentation took place, and pebbles and larger and smaller grains of all the three formations just mentioned, besides far-borne material of which the bulk of the rock is made, contributed to the composition of the conglomerates and sandstones of the Waterberg system, which now unconformably overlies these formations.

Much later, as one of the results of a powerful but local pressure from the south, all along the Hoekbergen and the edge of the Waterberg or Palala plateau, the lowermost strata of the Waterberg sandstone series and the fairly horizontal surface on which they

had been deposited were tilted at right angles or even overtilted. At Gatkop the effects of this pressure evidently attained a maximum. There a block of rocks belonging to the Transvaal system was pushed over the edges of the upturned strata of the Waterberg sandstone and the underlying Red Granite. The remnant of this block which has still escaped erosion now forms the summit of the picturesque Gatkop Peak. The thrust-plane on which this block rests ascends slightly toward the north. Below the thrust-plane the granite and the sediments were much sheared, and a succession of minor thrust-planes was formed parallel to the major one, constituting together a kind of imbricated structure.

The intrusion of the Red Granite is thus clearly anterior to the deposition of the "Upper" Waterberg, and hence also anterior to the powerful thrust from the south, which gave rise to the interesting disturbances so well disclosed at the eastern slope of Gatkop Peak.

The question remains to be answered: When did these disturbances occur?

The Upper Karroo beds in this portion of the Waterberg district are undisturbed. The Bushveld sandstone near Warmbaths has a nearly horizontal position, although on Buiskop it lies at a distance of only 6 miles from, and on the line of strike of, the disturbances of the Gatkop-Hoekberg type, which are much in evidence on the farms Zwartkloof Number 2126 and Roodepoort Number 2143. The Bushveld sandstone has been correlated with the Cave sandstone in the Orange Free State and the Cape Province, which is of Upper Karroo age.[1] Thus it may be accepted that the Gatkop-Hoekbergen disturbances are older than the Upper Karroo.

Further, it appears probable from the results obtained in a borehole put down on Buiskop, where at a depth of 365 feet the Coal Measure series has been struck below the Bushveld sandstone, that these disturbances are also anterior to the deposition of the Coal Measure series, which has been correlated with the Beaufort series of Middle-Karroo age. Concluding, the age of the Gatkop-Hoekbergen orogenic disturbances may be regarded as of post-

[1] H. Kynaston, "Note on the Correlation of the Bushveld Sandstone Series," *Trans. Geol. Soc. South Africa*, Vol. X (1908), p. 33.

Waterberg and pre-Middle-Karroo age. Whether they are also older than Lower Karroo is not yet known.

Thus these orogenic disturbances may have coincided with those which gave birth to the Cape Cordillera. The latter are known to be post-Lower Karroo, but their relation to the Middle Karroo has not been ascertained.

GENERAL CONCLUSIONS

1. All members of the Bushveld complex—norite, felsite-granophyre, coarse granite—as here defined, were erupted before the deposition of the "Upper" Waterberg conglomerates and sandstones. The youngest member, the coarse Red Granite, at Balmoral, and a quartz-porphyry, marginal phase of it at Gatkop are seen to underlie those sediments unconformably. The erosion interval represented was long enough to permit the removal of some hundreds of meters of strong rocks, including a considerable thickness of the Red Granite itself.

2. The magma yielding the main bodies of felsite reached the earth's surface as a huge flow or as a small number of thick flows. Extrusion seems to have been locally characterized by explosion, resulting in pyroclastic phases of the felsite. According to the conclusion of the Geological Survey staff, rather thick lenses of sediment, such as the shales of the Sterkstroom Valley and of the Middelburg district, were interbedded with the volcanics; if this be true, the volcanic activity lasted a comparatively long time and the felsite is not monolithic. In depth, or where the felsitic magma was intrusive into its own superficial, quickly chilled and solidified phase, this magma froze in the form of granophyre.

3. In greater depth was the enormous body of norite, from which the felsitic magma had been differentiated. The form of the norite mass, which, apparently, nowhere reached the surface, is analogous to that of a lopolith. In largest part its roof was the already chilled felsite-granophyre. Locally the norite underlies strata belonging to the Transvaal system and the Rooiberg series (probably the uppermost part of that system), but the felsite-granophyre-norite composite had no continuous sedimentary roof at all. Although at depth the norite magma was injected into the Transvaal beds,

the three-member composite may be looked upon as a colossal, differentiated lava-flow, resting on the surface of the centrally sunken, split, and injected strata of the Transvaal system. The extrusion may have been due to the foundering of the roof of a great sheet or lopolith—"areal" extrusion—following the differentiation of an injected mass.

4. At the outcrop the floor of the norite body is constituted of the Magaliesberg quartzite, though the many "diabase" sills beneath may possibly be offshoots from the same body of magma. (On the other hand, those sills may represent the main Bushveld magma in its chemical state just before the differentiation of felsite and norite; this delicate question must be left for future study.)

5. The main norite body had solidified to the depth of many hundreds of meters, if not entirely—a process in either case demanding much time—before the intrusion of the coarse Red Granite, which cuts the norite and granophyre in typically plutonic fashion. This granite occurs as dikes, cross-cutting, stocklike masses, and probably also as extensive sheets or laccoliths, in norite, granophyre, and Transvaal sediments. This youngest eruptive completes the list of components of the Bushveld complex, as here defined.

6. The writers conclude that it seems best to define the Waterberg system so as to include only those sediments which are now mapped by the Geological Survey of South Africa as "Upper Waterberg." The felsites and pyroclastic beds of the mapped "Lower Waterberg" belong to the Bushveld complex, and in large part indicate the place or places where the erupted Bushveld magma (felsite-granophyre-norite) was roofless.

7. Thus Molengraaff's earlier (1898) interpretation of the complex as volcanic (extrusive) is believed to be more nearly correct than his later suggestion, that the complex is a laccolith, roofed by the "Upper" Waterberg sandstone-conglomerate. At the same time it is clear that the deeper parts of the norite and the still deeper-lying "diabase" bodies have been emplaced after the manner of sheet or laccolith, and probably the same mode of emplacement has characterized certain extensive bodies of the coarse Red Granite. One is tempted to ask whether that other colossus, the gabbro-red rock complex of Minnesota, was not also in part roofless.

8. The Rooiberg sediments may represent the uppermost division of the Transvaal system, higher than the Magaliesberg quartzite. In some places the Rooiberg strata are highly metamorphosed and separated from the underlying sediments of the Pretoria series by the norite. In other places they are invaded by the Red Granite, and form its roof over considerable distances.

On the other hand, it is possible that the somewhat peculiar, feldspathized quartzites of the Rooiberg, mapped as separate blocks in norite or granite, may have been derived from several quartzitic horizons in the Transvaal system, having been floated up from their original positions in that system of sediments after or during the downwarping of these strata.

It may also be noted that no field evidence of unconformity between the Rooiberg series and the Pretoria series has been forthcoming. That the Rooiberg is older than the norite and therefore older than any part of the ("Upper") Waterberg system seems quite clear.

9. Long after the freezing of the coarse Red Granite, and after the deposition of much or all of the Waterberg series of sandstones and conglomerates, renewed eruptivity caused the injection of dikes and sheets of "diabase" into these sediments. Some of the sheets were gravitatively differentiated, with the generation of red felsite and granophyre, which are very similar to those of the Bushveld complex. The resemblance of the younger and older felsites and the resemblance of the younger and older granophyres are not surprising if the initial magmas of the two eruptive cycles had the same (basaltic) composition, and if the physical conditions were essentially the same during the two cycles. These assumptions are not unreasonable; they tend to simplify the stratigraphic situation in the Transvaal. The Bushveld complex belongs wholly to the first of the two petrogenic cycles.

10. The upturning and overtilting of the Waterberg strata (Upper Waterberg of the Geological Survey maps) at Gatkop, Rhenosterkop, and elsewhere, are probably products of the same succession of strong orogenic disturbances which later became responsible for the origin of the cordillera of the Cape Province. This cordilleran phase of the South African deformation is known to be post-Lower Karroo and pre-Cretaceous.

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POST-PLEISTOCENE VOLCANICS OF THE BRITISH COLUMBIA COAST

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ABSTRACT

In 1921 and 1922 the writer discovered ten separate post-Pleistocene extrusions on a group of coast islands in the vicinity of Milbank Sound, about 340 miles north of Vancouver. Both tuffs and lavas are described in detail. The post-glacial age of the tuffs is shown by the fact that they rest on glaciated surfaces and on deposits of till and contain in their basal members many large glacial bowlders which rest on the underlying granodiorite.

During the summer of 1921 and 1922, while the writer was engaged in making a geological map of the shoreline of British Columbia between latitude 52 and the Alaskan boundary, volcanic rocks of post-Pleistocene age were discovered. The chief interest in this discovery is that it adds another link to the almost continuous chain of active and recent volcanoes which encircles the Pacific Ocean. While this is the third discovery of recent vulcanism in the British Columbia section of the Pacific shoreline, very little has been published concerning these occurrences and their existence is little known even among petrographers.

The first post-glacial volcanics discovered in the coast region of British Columbia occur on the Naas river 38 miles above its entrance into Portland Inlet. These were discovered in 1892 by James McEvoy[2] who describes them as several small basaltic flows which apparently flowed down a valley lying to the south and now occupied by Lava Lake. He believes that the flows are not more than 200 years old. This locality was visited during the summer of 1922 by George Hanson, of the Geological Survey of Canada, and a more complete description of the occurrence will be published by him in the *Summary Report of the Geological Survey* for 1922.

[1] Published by permission of the Director, Geological Survey, Ottawa, Canada.

[2] James, McEvoy, *Geol. Surv. Can. Summary Report*, 1893, pp. 14A.

The second discovery of post-glacial volcanics in this part of the Pacific Coast was made in 1913 by E. M. J. Burwash.[1] These volcanoes are situated in the Mount Garibaldi district about 40 miles north of Vancouver. In this vicinity there are two cones of basalt and one of tuff. The highest cone forms the peak of Mount

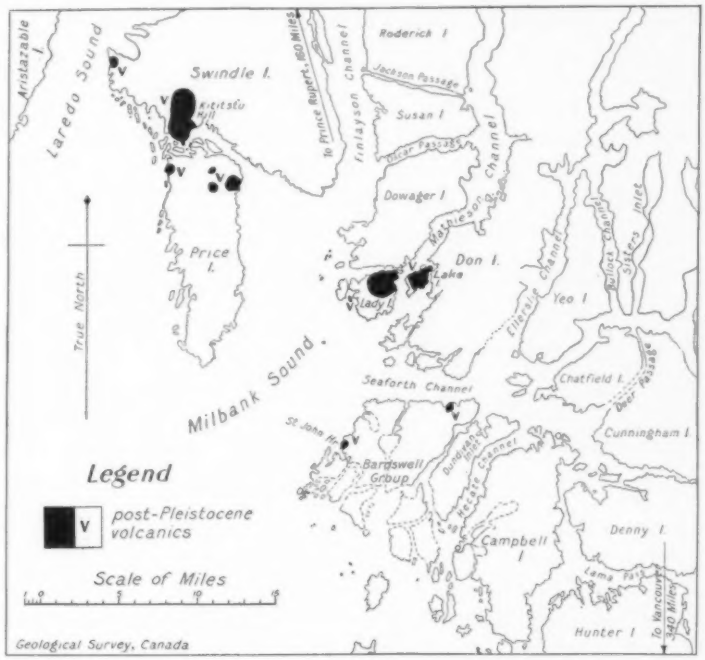

FIG. 1.—Diagram showing distribution of post-Pleistocene volcanoes in the vicinity of Milbank Sound, coast and islands of British Columbia.

Garibaldi, which is the highest mountain of the district, having an elevation of 8,700 feet. Recent flows believed to have originated in this center occur on the shore near the head of Howe Sound and are mentioned in a report[2] by Charles Camsell.

[1] *Geology of Vancouver and Vicinity.* University of Chicago Press, 1918.

[2] *Summary Report, Geol. Surv. Can.*, 1917, Part B.

In 1908 while engaged in mapping the shoreline of Queen Charlotte Sound, R. P. D. Graham discovered a small area of coarse breccia containing bowlders of granodiorite up to 2 feet in diameter that had a strong tendency to exfoliate. Graham considered this breccia to be of Tertiary age. The locality was visited in 1922 by the writer who, in view of the other discoveries and certain other evidence, believes this breccia to be of post-Pleistocene age.

DISTRIBUTION AND EXTENT

The volcanic rocks discovered by the writer in 1921 occur in small areas on some of the islands in the vicinity of Milbank Sound,

FIG. 2.—North end of Price Island and the south end of Swindle Island, looking west and showing two volcanic plugs on Price Island and volcanic cone (Kititstu Hill) on Swindle Island.

about 340 miles northwest of Vancouver and about 160 miles south of Prince Rupert (Fig. 1). They appear at or near sea-level and are arranged close to the boundary between the two principal physiographic divisions of the district. To the east of this boundary rises rather abruptly the rugged and lofty Coast Range of British Columbia, while to the west lies a low rolling plain with an average elevation of less than 200 feet, which is well illustrated in Figure 2.

Though these extrusions are scattered along a line 25 miles in length, they cover very limited areas. Ten extrusions were discovered, but as only the shorelines were examined others probably exist in the interior parts of the islands. Two of those examined consist of tuff, while the others are of basic lava, usually porphyritic.

The tuffs occur on Lake and Lady islands and cover a total area of not more than 4 or 5 square miles. On Lady Island they have a thickness of about 50 feet, and on Lake Island they form a steep cone about 1,000 feet high. The largest extrusion of lava occurs on the south of Swindle Island near Kititstu Hill. This is a lava cone about 600 feet high. To the north of it there is a lava field 3 or 4 miles in length and of unknown width. These flows have a thickness of at least 200 feet. They are shown in Figure 2.

TUFFS

The tuffs are confined to Lady and Lake islands in Milbank Sound at the mouth of Mathieson Channel. Those on Lake Island form a steep cone 1,000 feet high. The island, however, is less than 2 miles in length and as there is a considerable portion of the south side unoccupied by the tuffs, it is evident that their area is very small in comparison with the elevation of the cone. For this reason it is thought probable that much of the cone is composed of a quartz diorite hill on which the tuffs form a covering not more than several hundred feet thick. Vertical cliffs of tuff 400 feet high do, however, occur on both the east and west sides of the cone. On Lady Island, 1 mile to the west, the tuffs occupy a greater area, but have a maximum thickness of probably not more than 60 feet and occur at elevations not greater than 75 feet. As these tuffs are of post-Pleistocene age and cannot therefore have been greatly affected by denudation, it is evident that the volume of material extruded was exceptionally small.

Lithology.—The tuffs composing the cone on Lake Island are massive and unstratified in the upper central parts of the cone, but in the lower and marginal parts they are well stratified. The massive tuffs of the central part are medium fine and even grained, have a yellowish brown color, and contain no fragments or pebbles of foreign rocks. Under the microscope they are seen to consist almost entirely of fragments of highly vesicular yellowish glass containing microlites of feldspar and augite and spherulites, the latter being composed of radiating blades of feldspar and chlorite. The glass has an index of 1.59 which is almost the same as that of artificial glass made from basalt. There are also a few fragments of

labradorite and augite. The labradorite is perfectly fresh and clear, and most of the grains have smoothly rounded outlines. The augite has a clear bottle-green color in hand specimens and is colorless under the microscope. A few fragments of dark green hornblende were also observed.

The stratified tuffs along the shore are much more heterogeneous in character and contain numerous pebbles and boulders of quartz diorite. The bowlders range in size up to 6 feet in diameter, the larger ones being confined to the very base of the formation. Most of them, such as that shown in Figure 3, lie on the underlying quartz-diorite and are buried in the tuffs. Others, however, such as that in Figure 4, rest in the tuffs a few inches, or feet, above the base of the formation. Pebbles of quartz-diorite are found as high as 30 feet from the base of the tuffs. These are both rounded and angular, and were caught in the force of the explosion and hurled into the air with the other material. The large bowlders frequently have a strong tendency to exfoliate, many of those exposed being surrounded by thin curved shell-like fragments which have fallen off. They are considered by the writer to be glacial bowlders which have been buried in the hot tuffs and themselves heated to a sufficiently high temperature to cause the exfoliation.

FIG. 3.—Glacial bowlder of quartz-diorite buried in tuffs and resting on the underlying surface of quartz-diorite.

The tuffs on Lady Island are, on the whole, coarser-grained, more heterogeneous, and more generally but roughly stratified, as is shown in Figure 5. Quartz-diorite pebbles and bowlders are much more plentiful than in the Lake Island tuffs, and are more generally distributed. In several places the tuffs rest on coarse

till, and in other places on numerous large bowlders which almost cover the underlying quartz-diorite. The tuffs themselves consist

FIG. 4.—Bowlder of quartz-diorite buried in tuffs 12 inches above the base of the tuff

FIG. 5.—Bedded tuffs on east side of Lady Island, showing depositional dip seaward

of a dull grayish brown groundmass containing, besides the above-mentioned pebbles, rounded lapilli and bombs, angular fragments of yellowish brown glass, a few calcite amygdules, numerous

rounded grains of glassy feldspar, considerable augite and minute quantities of quartz and hornblende. Under the microscope the groundmass is seen to consist chiefly of glass fragments grading in size down to submicroscopic, with small amounts of the above-mentioned minerals. The glass is highly vesicular and usually contains many microlites of labradorite and augite (Fig. 6). The

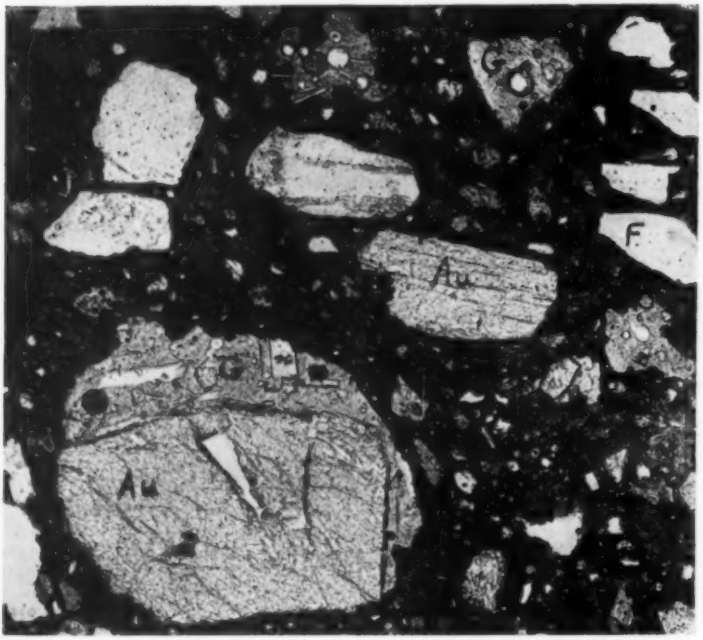

FIG. 6.—Thin section of tuffs from east shore of Lady Island, showing fragments of augite (Au), feldspar (F), and vesicular and glass with microlites (G) frozen to augite crystal. Magnified 150 diameters. Au=augite. G=glass. F=feldspar.

lapilli are of two colors, brown like the glassy groundmass and black due to the presence of a large proportion of magnetite. Many of the augite phenocrysts have shells of glass frozen to them such as the one shown in Figure 6. The labradorite is exceptionally clear and pure, and has a composition of Ab 42, An 58.

Relation to older rocks.—Both on Lady and Lake islands the tuffs were found resting on the quartz-diorite of the Coast Range batholith, which is the only other formation occurring in this district. In four different localities the tuffs were observed lying on what are unmistakably glaciated surfaces. Two of these localities are shown in Figures 7 and 8. At another locality the tuffs rest on what appeared to be a bed of till. In many other

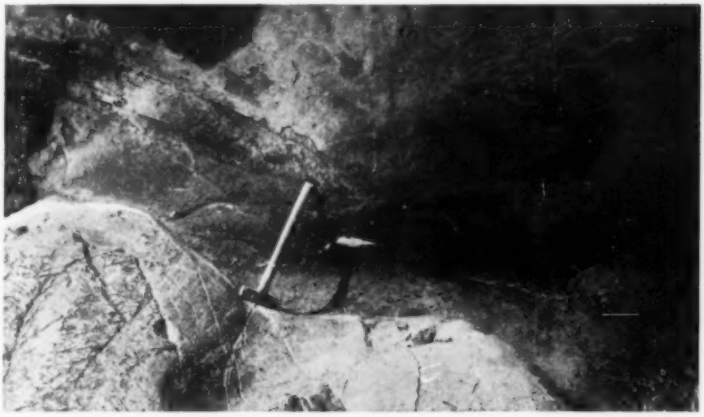

FIG. 7.—Tuffs resting on glaciated surface of quartz-diorite, east shore of Lady Island

places, where the base of the tuffs is exposed, large bowlders up to 6 feet in diameter were found resting on the underlying quartz-diorite and buried in the tuffs. Some of these showed a strong tendency to exfoliate. All of these phenomena indicate that the tuffs are of post-Pleistocene age.

LAVAS

The lavas occur as small flows, plugs, and, at Kititstu Hill, Swindle Island, as a cone 600 feet high with horizontal flows extending from the base for several miles to the north. The small intrusions occurring on the west shores of Swindle, Price, and Lady islands, and on the north of the Bardswell group, are each only a few hundred square yards in extent and only several feet in thickness. They are somewhat circular in shape and occupy small

depressions near the shore at practically sea-level. Some, at least, are connected with feeders from below but owing to the position of the outcrops these are not exposed. All of them have a well-developed columnar jointing (see Fig. 9) which, in most cases, is perpendicular to the present surfaces of the flows and to the surface on which they rest. In the central part of the small flow on the north shore of the Bardswell group the columns are arranged in a large circle and dip at angles from 45 to 75 degrees toward the center, which seems to suggest that a pipe-shaped feeder projects downward from this point. The extrusion on the west shore of Lady Island forms an elongated dome about 150 yards in length. The glassy lava composing it has a columnar jointing on rather a small scale, the columns having an average diameter of 4 or 5 inches. These stand perpendicularly to the surface of the dome. The plugs on Price Island shown in Figure 2 are also jointed but to a less marked degree.

Lithology.—The lavas consist of dark gray to dense black, basic andesites and basalts. They are fine-grained but usually well crystallized, and except in one case, contain only small amounts of glass. Amygdaloidal lava is found in only one locality, on the north side of Kititstu Hill, Swindle Island, but here it is extremely vesicular. Many of the flows are porphyritic containing phenocrysts of glassy feldspar up to $\frac{1}{4}$ inch in length. These are, however, never abundant and in some flows there are not more than one or two to the square foot. For purposes of description they may be divided into basalt, andesite, and glassy andesite, the latter found only on the west of Lady Island.

The basalt is very fine-grained, has a dense black color and contains only a very few feldspar phenocrysts. The groundmass consists mainly of feldspar laths and augite with an unusually high proportion of magnetite, which gives them their dense black color. Small amounts of olivine, serpentine, and apatite are also present. The serpentine occurs in amygdules and in veins in the olivine. The phenocrysts are plagioclase, augite, and olivine, the latter being decidedly rare, and the others only sparsely present. The plagioclase phenocrysts are up to $\frac{1}{2}$ inch in size, are perfectly fresh and clear, generally idiomorphic and usually slightly zoned. The

composition varies within a narrow range from basic andesine to andesine-labradorite, the average composition being about Ab 48

FIG. 8.—Tuffs resting on glaciated surface of quartz-diorite, east shore of Lady Island, showing depositional dip.

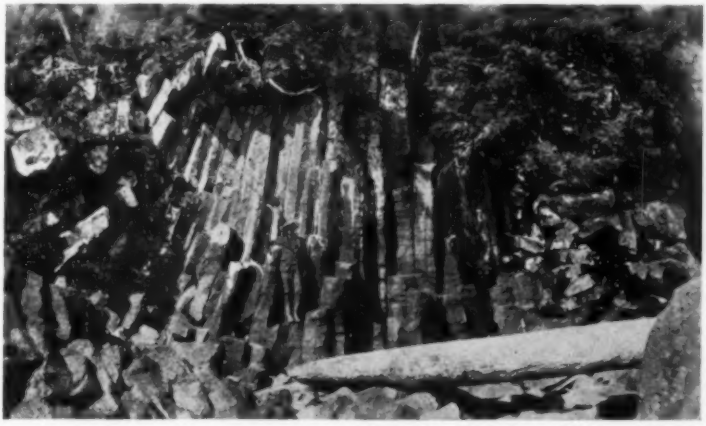

FIG. 9.—Columnar jointing, east shore of Lady Island

to An 52. The augite phenocrysts are somewhat smaller; they are also highly transparent having a bottle-green color in hand specimen and a very faint green in thin section. The olivine is

fairly fresh but contains a few veins of serpentine and is slightly colored by iron. The crystals are optically negative and, therefore, probably contain more than 12 per cent of FeO. The glass is of a dark brown color and occupies intercrystal spaces and small veinlets in the phenocrysts.

The basic andesites are more abundant, and compose the major part of the larger extrusions, such as the plugs on Price Island, and the cone and attendant flows of Kititstu Hill, Swindle Island. They have a grayish color, contain many feldspar phenocrysts and much glass, and are in places highly vesicular. A typical example is the rock composing the most southerly of the plugs on Price Island. It is a grayish, medium fine, highly porphyritic rock, with numerous miarolitic cavities. The groundmass consists of andesine laths and augite rods with a small proportion of magnetite in the form of finely branching crystals. A considerable amount of apatite is invariably present in all these rocks. The phenocrysts are andesine-labradorite, augite, and olivine. The feldspar is very abundant, is perfectly transparent, and occurs as idiomorphic crystals up to $\frac{1}{2}$ inch in length. The augite phenocrysts are less abundant and smaller in size and seldom idiomorphic. The olivine is about equal in amount to the augite, and many of the crystals are partly altered to serpentine, while others are quite fresh. They have a negative optical character indicating over 12 per cent FeO. The andesite of the Kititstu Hill cone is similar to the above, but instead of the miarolitic cavities, it contains an unusually large number of gas cavities up to $\frac{1}{2}$ inch in diameter. In places these vesicles are so numerous as to give the rock an appearance similar to that of an ordinary sponge.

The glassy andesite forming the small dome-shaped extrusion on the west shore of Lady Island differs considerably from the other rocks. It is composed of a light-yellow glass containing microlites of feldspar and pyroxene and probably some olivine, but this last mineral could not be positively determined owing to the minuteness of the crystals. The feldspar has the composition of andesine. The glass has an index of refraction of about 1.545 which is lower than that of the glass of the other rocks. These two facts indicate that this extrusion is of a more acid composition and more nearly that of a normal andesite.

Relation to older rocks.—The relation of the flows to the underlying rocks is not so clearly shown as that of the tuffs and their age, therefore, not known with such certainty. The following facts, however, prove them to be of recent geologic date and probably of post-Pleistocene age. All the flows rest on the quartz-diorite of the Coast Range batholith. The upper surfaces of the flows are perfectly horizontal, while the lower surface in each case conforms to the irregular surface on which it rests. The two plugs shown in Figure 2 project almost perpendicularly from the strongly glaciated surface of Price Island. The quartz-diorite surface surrounding the plugs shows many evidences of glaciation and the striations indicate that the ice moved in a southwest direction. The plugs themselves show no signs of glaciation. The northeast side (the right side in the photograph) which faces the direction from which the ice advanced is as perpendicular as the southwest side. No moraine trails off from the southwest or protected side. The tops of the plugs are exceedingly jagged and strewn with large angular blocks of the andesite of which they are composed. Two such isolated and unmodified protuberances could hardly have existed prior to the glaciation which scoured the surface of Price Island. The cone forming Kititstu Hill is likewise unaffected by ice erosion. These facts together with the close proximity and lithological similarity to the post-Pleistocene tuffs suggest that the lavas are of very recent and probably post-Pleistocene age.

RECENT VOLCANIC DYKES

There are in the coast region of British Columbia, besides these recent volcanoes, an immense number of dykes of comparatively recent geologic date, some of which are thought to be in some way related to the lavas. The great majority of these dykes show many of the characteristics of rocks which have suddenly solidified, like lava flows, under the conditions of low temperature and pressure which obtain at or near the surface. Many of them contain glass and some of them, up to 12 feet in width, are composed entirely of volcanic glass with a few spherulites and microlites. Many of them have an unusually well-developed columnar jointing in many cases more perfect than that of the flows. Other features of surface flows such as amygdules, spherulites, petlitic structure, nodular

structure, miarolitic and flow structures are very commonly present in these dykes. Their compositions cover a wide range from acid rhyolite to basalt. The most common type and the one most widely distributed throughout the coast region, has a composition close to a normal andesite and very strongly resembles the flows just described. It is brownish-black, weathers to a light brown, and generally has an unusually well-developed columnar jointing. It consists of a fine-grained groundmass of andesine-labradorite, augite and brown glass, containing rather plentiful phenocrysts of clear amber-colored feldspar similar in composition to that of the groundmass, and a few shattered phenocrysts of equally transparent green augite. There are few dykes more basic than this common type, but a great many of a more acid composition. Both trachytes and rhyolites are quite common.

In the vicinity of Denny Island and the Bardswell group there are literally hundreds of these late dykes, so closely spaced in places as to replace completely the older rocks which they intrude. Many of the dykes of this vicinity have an unusual composition placing them in the classes of soda-rhyolites and soda-trachytes, along with such rare types as comendites and pantellerites and paisanites. These dykes are particularly glassy and those which consist entirely of glass are probably of these types. They consist of such minerals as oligoclase, albite, microcline, anorthoclase, aegirine-augite, aegirine, riebeckite, arfvedsonite, and in one specimen were found some beautifully developed, though minute, crystals of aenigmatite. One of these was extracted from the rock and its crystal angles measured by Dr. E. Poitevin, of the Mineralogical Division of the Geological Survey. The triclinic character and some of the characteristic forms of aenigmatite were thus recognized and the microscopic determination of the mineral so confirmed.

The following is an analysis of a specimen of the volcanic glass containing a few microlites of aegirine and probably some riebeckite, made by M. F. Connor.

SiO_2	70.50	K_2O	4.28
Al_2O_3	9.85	H_2O	6.07
Fe_2O_3	1.02	TiO	0.20
FeO	3.12	P_2O_5	Trace
MgO	0.07	MnO	0.14
CaO	0.36		
Na_2O	4.57		100.18

GENERAL FEATURES OF PRE-CAMBRIAN STRUCTURE ALONG THE BIG THOMPSON RIVER IN COLORADO[1]

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ABSTRACT

This paper discusses the relations between the pre-Cambrian schists (sedimentary) and the granites and pegmatites with the accessory dike rocks exposed along the eastern flank of the Front Range in the Big Thompson River valley. The Longs Peak granite makes up great stocks and bathyliths intruded into the upwarped and dislocated beds of the Big Thompson schist. The Mount Olympus granite intruded the Big Thompson schists and the Longs Peak granite in similar stocks and bathyliths. A wealth of pegmatite dikes transect all of the series. Faults are rare, although of several types. Near the foothills the faults are related to the *en échelon* folding of the foothill sediments. In the granites they are mostly normal from tension. Around Longs Peak they appear to be low angle overthrusts.

INTRODUCTION

The Big Thompson River Valley occupies the eastern flank of the Front Range in north central Colorado (Fig. 1). The pre-Cambrian structures occupy parts of the Longs Peak, Mount Olympus, and Loveland quadrangles.

The recent arching of the Front Range located its crest at the present continental divide and determined the easterly direction of slope of the drainage basin of the Big Thompson River. The western slope of this range descends to Middle Park and dips to the west under the overlapping edges of Cretaceous sediments (Fig. 2). At the eastern margin of the Front Range the foothill beds, which are unaltered Mississippian, Jurassic, and Cretaceous sediments, dip to the east with angles of less than twenty degrees, where least disturbed, to nearly vertical where the strata are associated with *en échelon* folding and faulting. Directly north

[1] Field investigation of the general geology of the Big Thompson River Valley occupied the summers of 1921 and 1922. The results of the work are incorporated in the "Geology of the Big Thompson River Valley in Colorado," accepted at the University of Chicago in partial fulfillment of the requirements for the degree of Ph.D. This paper deals with one of the topics included in the report.

of the Big Thompson River's course across the foothills the strata have been arched and thrust against the flank of the Front Range in a marked north to south fold, accompanied by faulting. Subsequent erosion has disclosed an offset and dislocated mass of granite and schist such as is characteristic of the core of the range

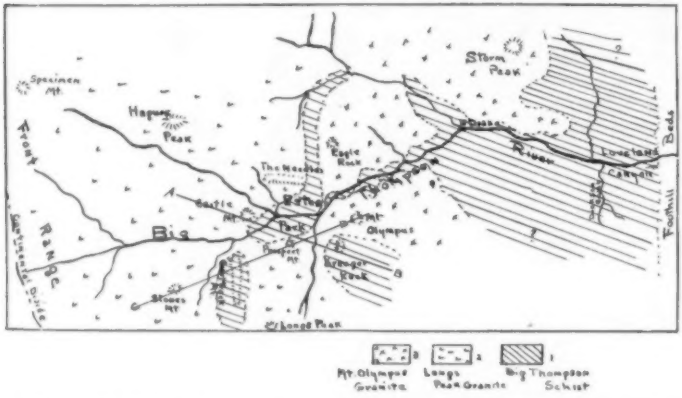

FIG. 1.—Sketch map to show the Big Thompson River Valley in north central Colorado. The boundaries of the rock formations are roughly indicated, but only the major outcrops are here outlined.

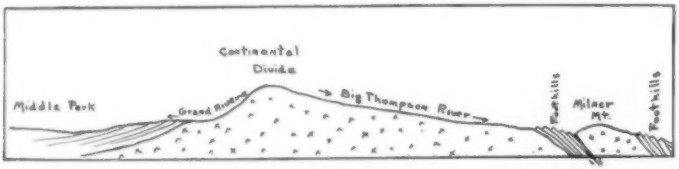

FIG. 2.—Generalized cross-section through the Front Range showing the relations of the pre-Cambrian with the Carboniferous, Jura-Trias, and Cretaceous sediments of the foothills on the east and the Cretaceous beds of Middle Park on the west.

but isolated from it and considerably farther east. Thus Milner Mountain stands out as a crystalline mass nearly surrounded by upturned sediments.

Similar faults and folds are repeated along the border of the foothills district to the south. This discussion will be limited, however, to the features of structure involved in the relationships

of the granites, pegmatites, and schists with the accessory rocks making up the bulk of the pre-Cambrian strata.

STRATIGRAPHY—GEOLOGIC COLUMN

CENOZOIC

Quaternary. Recent—terrace gravels and talus.

Pleistocene

2. Late Wisconsin drift, moraines, grouns, lateral, terminal.

1. Early Pleistocene ground moraine, reworked river and glacial gravel.

Unconformity

Tertiary

3. Rhyolite dikes in Bjg Thompson schist and Longs Peak granite.

2. Andesite flows, dikes, and breccia in the schist and Longs Peak granite.

1. Basic dike rocks intruded into schist and Longs Peak granite.

UNCONFORMITY AND INTRUSIVE CONTACT

PRE-CAMBRIAN[1]

Proterozoic

5. *Pegmatites* are tourmaline- and garnet-bearing dikes with great variety of size and texture cutting the Big Thompson schists, the Mount Olympus granite, and the Longs Peak granite. Their chief area lies between the Mount Olympus granite and the Big Thompson schist and is intrusive into both. The dikes vary from quartz-rich stringers and paper-thin layers in the schist, through coarsely crystalline, sharply defined masses of quartz, feldspar, muscovite, and biotite or tourmaline several feet across, to medium

[1] The oldest unmetamorphosed sedimentary beds resting on the series of granites and schists designated as pre-Cambrian in this study are the Fountain conglomerates of Mississippian age (see *Colorado Geological Survey*, 1908). To the south, in the vicinity of Colorado Springs, beds of Cambrian age (Middle) overlie a similar series of granites and schists in a like position. See *U.S. Geol. Survey Atlas Folio No. 203*. Since this crystalline core of the Front Range appears to be continuous from north to south throughout Colorado, it is likely that it is all pre-Cambrian. The granites and schists are tentatively assigned to the Proterozoic since the granites are fresh and little altered and the schists include great amounts of very little metamorphosed sediments and some thin beds of unchanged conglomerate.

coarse dikes of granitoid texture welded into and merging with the granite wall rocks.

4. The *Mount Olympus granite* is a fine-grained, gray biotite granite cutting the Longs Peak granite and the Big Thompson schist. It is named for the peak and quadrangle over much of whose surface it is exposed and lies to the east of the main area of the Longs Peak granite. It welled up as a barrier separating the Longs Peak granite from the less metamorphosed parts of the Big Thompson schist. It may be readily distinguished by its characteristic rectangular, regular, and sheetlike jointing. The contacts between the Mount Olympus granite and the Big Thompson schist are clean cut, angular, and marked by numerous indurated, unabsorbed fragments of schist lying within the granite close to the contact.

3. *Pegmatite* is a coarse, yellowish pegmatite cutting the Longs Peak granite and the Big Thompson schist. It is probably related to the Longs Peak magma and is confined to the area of the continental divide.

2. *Longs Peak granite* is a coarse, pinkish granite with well defined tabular crystals of feldspar. It is named for the famous peak, a large part of whose bulk is made of this porphyritic granite intruded into the Big Thompson schist. The chief exposures lie along the continental divide where it contains up to 10 per cent of sillimanite and is locally gneissoid, especially where developed in great stocks and bathyliths. Weathered surfaces exfoliate in thin concentric shells. Locally it is thinly veneered with Big Thompson schist or includes masses of the schist whose contacts are frayed and torn where the granite and schist feather out into each other.

1. The *Big Thompson schists* are a series of metamorphosed sandstones, shales, and limestones with a small amount of conglomerate. These rocks comprise the older surface exposures in the area and are named for the Big Thompson River which, in traversing the eastern slope of the Front Range, has exposed a complete section of the schist in all its wealth of variety and extent of metamorphism. The strata are a series of interbedded metamorphosed crystalline rocks derived by regional and contact metamorphism

against granites which cut through the schists in stocks, bathyliths, and numerous dikes. There is a definite regular gradation of the Big Thompson schists from the highly metamorphosed, dense black biotite-sillimanite schists of the continental divide and Estes Park region eastward through quartz-biotite and chlorite schists to pure quartz schists in the Loveland Canyon.

All the diverse phases are interbedded, show transition varieties, and, although clearly graded from west to east, are undoubtedly parts of the same formation. In general, the schistosity is parallel to the original bedding of the sediments.

STRUCTURE OF THE PRE-CAMBRIAN ROCKS

A. STRUCTURAL RELATIONS WITHIN THE BIG THOMPSON SCHISTS

The sediments from which the Big Thompson schists were derived appear to have been laid down in a more or less embayed sea which occupied the area of the present Front Range in pre-Cambrian times. The coarsely crystalline character of most of the schist and gneiss, together with a computed thickness aggregating over 4,000 feet for some of the exposures, indicate that the basal beds of this series were deeply buried. Hence the detached and fragmentary masses of schist now exposed in the area are remnants of a thick series of sediments which was continuous from east to west across the Big Thompson area.

As a result, the beds of biotite-sillimanite schist in contact with granite in the region of the continental divide were derived from argillaceous sediments contemporaneous with the quartz schist which was derived from sandy beds to the east. These two chief types of rock grade into each other and are locally interbedded.

The schist of the Estes Park region shows much more intense metamorphism than that in the Loveland Canyon area. The thinly laminated, muddy character of the original sediment, combined with its intimate injection and almost complete saturation by pegmatite magma under the influence of two successive magmatic invasions, is responsible for present altered conditions. On the other hand, the typical schist of the eastern area is almost entirely free from minor crumpling; the layers maintain their integrity and parallelism for considerable distances although the whole formation

stands nearly vertical wherever exposed (Fig. 3). This portion of the schist was subject to the influence of only one of the granitic invasions and its original high percentage of sand offered less opportunity for the development of new minerals.

The initial metamorphism of these sediments was accomplished by the intrusion of the Longs Peak granite. It appears that the invasion warped the partly indurated sediments and lifted the surface of the sedimentary series to unknown heights. A little later the Mount Olympus granite entered the already greatly disturbed, highly heated region so that tourmaline penetrated through hundreds of feet of sediments, where it crystallized in minute crystals within the quartz schist.

The present altitude of the schist beds is largely due to the warping as a result of the successive intrusion of two magmas into these early sediments.

B. STRUCTURAL RELATIONS OF THE GRANITES AND SCHISTS

Both the Longs Peak granite and the Mount Olympus granite form huge stocks and bathyliths in the Big Thompson schist. The Longs Peak granite as the older of the two invaded the schists, in places dislocating and rupturing the strata, and in others invading them along bedding planes in *lit par lit* injection. Most of the granite came to rest in dome-like bathyliths, arching the schist above them and upturning the beds around the flank of the domes.

In much the same way the Mount Olympus granite invaded and upturned the schist, ruptured and cross-cut the Longs Peak granite, and came to rest so as to occupy the eastern half of the area. It lies between the main area of the Longs Peak granite along and east of the continental divide and the main mass of the schist.

Thus stocks and bathyliths of two granites are associated with more or less highly metamorphosed schists, and the whole complex is repeatedly dissected by many kinds of granite and pegmatite dikes.

1. *Structural relations of the Longs Peak granite and the Big Thompson schist.*—The centers of many of the more conspicuous stocks and bathyliths of Longs Peak granite may be approximately determined by a study of the remnants of schist left lying on their flanks. For the most part the small patches of schist are all that

A

B

FIG. 3.—*A*, Biotite-sillimanite schist in the vicinity of Estes Park. *B*, Quartz schists of the Loveland Canyon.

is left of great thicknesses of sediments which were intruded by the granite. In a general way the foliation of the schist corresponds to the original bedding of the rock and commonly dips away from the centers of granite intrusion.

Prominent stocks of Longs Peak granite have been determined at many places (Fig. 1.):

a) At Prospect Mountain the schist dips away from the granite core on three sides at angles from twenty-five to eighty-five degrees. To the south the granite is confluent with that of Lily Mountain and The Crags.

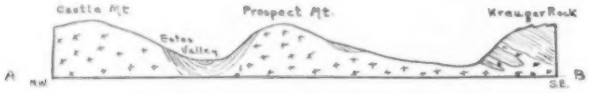

FIG. 4.—Structure section to show the Estes Valley syncline between the granite stocks of Prospect and Castle mountains.

FIG. 5.—Structure section to show the Gianttrack syncline of Big Thompson schist between stocks of Stones and Prospect mountains.

b) North of Estes Park village there is a compound dome centering around the Needles so that the schist under the village lying between Prospect and the Needles is a nearly closed syncline (Fig. 4).

c) The granite core of Stones Mountain has patches of schist dipping to the north and east but on the southeast the granite is confluent with that of the mountains to the south. The intrusion of granite into the Stones Mountain region together with the simultaneous invasion of the Prospect Mountain area developed a well-defined syncline now visible in the injected, highly foliated, and indurated schist of the Gianttrack–Teddy's Teeth area. The trough of the syncline, however, lies to the east of the crest of the mountains showing a steeper dip on the eastern limb than on the western. The axis of the trough emerges to the north end of Gianttrack Mountain and flattens out to the south around Lily Mountain (Fig. 5).

d) There is a similar area of stocks to the north and west in the vicinity of Hagues Peak and the Mummy Mountains but their general centers and surface relations are not yet carefully studied.

None of the stocks of Longs Peak granite are entirely isolated from each other. They are probably continuous at a greater or less depth as they may be readily traced in places by surface exposures. Thus granite may be traced continuously around the Giant-track syncline. The whole granite mass appears to be bathylithic and belongs to one or two general masses which are nearly simultaneous in origin. Their outlines broaden and deepen to unknown depths.

It appears that the Longs Peak granite ascended into the schist so as to crystallize in stocks and bathyliths. As it rose it bulged up the schist, ruptured it in many places, engulfed fragments of all sizes, and generally dislocated the beds into which it came. The intrusion was so intimate in many places that an injection gneiss was developed on an extensive scale. The granite magma invaded the schist so completely that the schist contacts with the granite are indistinct and the two rocks feather out into each other.

2. *The structural relations of the Mount Olympus granite, the Longs Peak granite, and the Big Thompson schist.*—The Mount Olympus granite has a similar bathylithic relation to the schist. It cuts through the Longs Peak granite in numerous dikes along the continental divide. To the east of Estes Park the dikes are more numerous as the contact with the main mass of the Mount Olympus granite is approached. The schist associated with this granite is considerably less indurated and injected than that around and within the Longs Peak granite.

Several huge stocks have been identified (Fig. 1):

a) Around Eagle Rock north of Loveland Heights there is a great stock in contact with the Longs Peak granite on the north and west, overlapped by schist along the course of the Big Thompson to the south and east.

b) Mount Olympus, Pisgah, and the region two or three miles east reveal a great bathylith of very irregular outline. North of this mass the schist along the river dips to the north at a high angle.

c) Storm Peak is the center of another granite mass which is responsible for the steep dips of the schist along the Big Thompson to the south and east.

d) There is a great exposure of the schist which lies along the river and adjacent to the foothills and dips to the southeast. At the contact with the Fountain conglomerate of the foothills the schist passes under the eastward dipping beds, maintaining its angle of seventy to eighty degrees all along the foothills even to the state line on the north.

So persistent a dip over a great area suggests a rock mass to the northeast against which these beds now lie buried under the foothill sediments. This may be a granite bathylith similar to those to the west or it may be the old land mass from which the

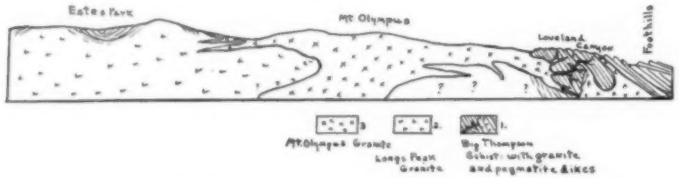

FIG. 6.—Section sketched to show the general field relations of the granites and schist. Note that the Mount Olympus granite separates the Longs Peak granite from the main mass of the Big Thompson schist.

sediments of the schist were derived and against which they were thrust and crowded into steep dips by the up-welling of the granite to the west.

The evidence reveals that the Mount Olympus granite entered the Big Thompson region so as to occupy the area at the eastern border of the Longs Peak–Big Thompson schist contact; it now lies in great bathyliths separating the surface exposures of the less indurated schist from the main mass of the Longs Peak granite adjacent to the continental divide (Fig. 6).

3. *Structural relations of the granites, pegmatites, and schist.*—The Big Thompson schist, the Longs Peak granite, and the Mount Olympus granite are repeatedly dissected by pegmatite dikes ranging from hairline stringers of quartz to broad massive dikes of granitoid texture. The contact walls may be welded, angularly shattered,

feathered out, or clean cut over long distances. The dikes may maintain their integrity, if not their content, for many feet or may branch freely within a few inches.

In general, the most varied mineral content as well as the greatest variety of size and thickness of the pegmatites is associated with the Mount Olympus–Big Thompson schist contact in the vicinity of Drake along the canyon. Here the river and its tributaries has disclosed a section several hundred feet deep and four or five miles at right angles to the general contact. Usually the wide, coarse pegmatite dikes in the schist carry large, greenish black, more or less perfect crystal aggregates of tourmaline and small, perfect, but rather rare garnets. The granitoid dikes with welded contacts are very common in the granite.

C. STRUCTURAL RELATIONS OF THE YOUNGER ROCKS OVERLYING OR PENETRATING THE PRE-CAMBRIAN BEDS

The younger rocks related to the pre-Cambrian beds may be classified into three groups:

1. Diorite and similar basic rock mostly in dikes cutting both schist and granites.

2. Andesitic and rhyolitic dikes, flows, and some tuff either lying on or penetrating the granites around Specimen Mountain.

3. Glacial drift and associated deposits resting on all types of bed rock.

The basic dikes follow schistosity planes or fill joint cracks in the granites. The leucocratic dike rocks are associated only with the Longs Peak granite. These structures seem to be the eastern outposts of more extensive deposits to the west of the continental divide and are related to the Tertiary vulcanism to the southwest.

FAULTS

In general the faults are of three types: (1) Those associated with the granites and probably resulting from tension due to the recent arching along the crest of the Front Range; (2) those associated with the schist either as overthrusts or a movement along bedding and schistosity planes, particularly in the Loveland Canyon; and (3) those related to the foothills deformation along *en échelon* folds.

A. NORMAL FAULTS DUE TO TENSION IN THE GRANITES

The faults which traverse only the massive granites are not easily distinguished from ordinary joint cracks where the breaks are clean cut. It is believed that normal, sharply cut fractures are the rule, but a few breaks marked by slickensides, gouge, and shear zones with distributive fractures are evident at outcrops.

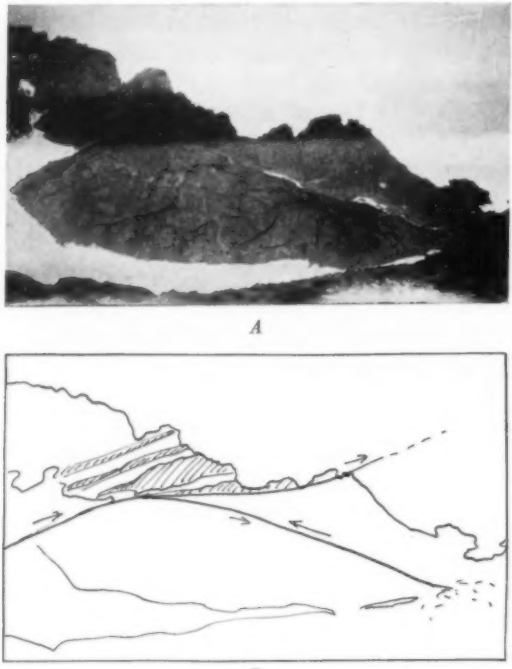

FIG. 7.—*A*, The eastern face of Longs Peak south of the Keyhole and above the Boulder Field. *B*, Suggested interpretation of possible fault lines in the area of *A*.

The Longs Peak granite is cut by dikes of the Mount Olympus granite at Castle Mountain and the whole dislocated by several small, nearly vertical faults with only a few feet of throw. There are many other less easily identified faults in both the Longs Peak granite and the Mount Olympus granite, all of which are either

simple fractures with poorly developed slickensides or distributive fractures adjacent to a major plane and mostly on the overhanging side.

B. OVERTHRUSTS IN BOTH GRANITES AND SCHISTS

There appears to be a series of faults associated with both schist and granite on Longs Peak. Above the Key Hole and to the south of the Boulder Field on the eastern face of the chasm, within five

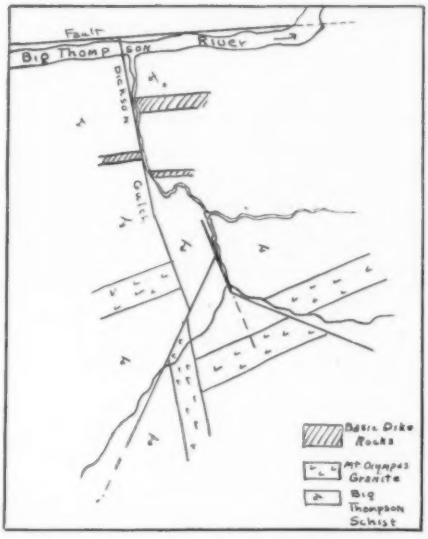

FIG. 8.—The faults along the course of Dickson Gulch which appear to have influenced the location of the stream channels.

hundred feet of the summit there appear to be two thrusts at a low angle (Fig. 7). The lower of the two seems to have thrust the upper part of the granite over onto the lower granite and interbedded schist in a plane about parallel to the general angle of the schistosity with considerable hade and little throw. The upper and later of the two faults appears to have shoved the top of the mountain (chiefly the schist) to the north over the already faulted beds below, but so as to intersect the lower fault at a low angle.

C. FAULTS RELATED TO THE FOOTHILL DEFORMATION

Faults are probably much more common in the schists than casual observation would suggest. Many of the dislocations were parallel to the schistosity and are evident only through the slickensides and shear zones parallel to the bedding. Some, in a general way, appear to be the sites of a few stream channels tributary to the Big Thompson (Fig. 8). The fault along Dickson Gulch appears to be related to the *en échelon* folding and faulting of the foothills region during the deformation which elevated the great anticlinal

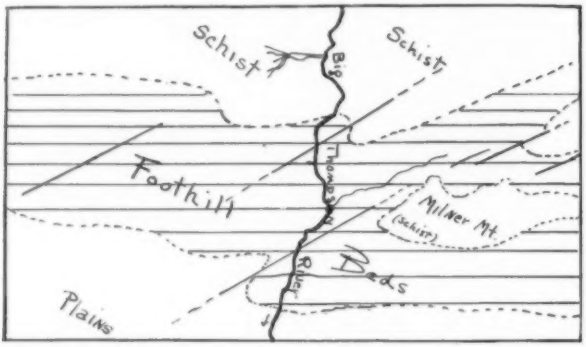

FIG. 9.—Faults related to the *en échelon* folding of the foothill beds adjacent to the Big Thompson schist. (Sketch adapted from map accompanying the *Colo. Geol. Survey, First Report*, 1908.)

arch prolonged from north to south through Colorado. In the vicinity of the Thompson River the faults have been mapped by the Colorado Geological Survey as in Figure 9. The exact extent to which these breaks have penetrated the granites to the west has never been accurately determined in most cases.

SUMMARY

The Front Range, along whose eastern flank lies the area concerned, is a great anticlinal arch of pre-Cambrian schists and granites. The features of structure along the beds making up the arch are related to the pre-Cambrian intrusion of stocks and bathyliths of the Longs Peak and Mount Olympus granites into the Big

Thompson schists of sedimentary origin. Both granites lie in huge stocks above and around which the sediments were arched and flexed, or cross-cut, by the rising magmas. Metamorphism begun by the Longs Peak magmas and accompanying diastrophism continued under the influence of the later Mount Olympus magmas so that the argillaceous materials of the continental divide area were converted into biotite-sillimanite schist and injection gneiss, and the arenaceous sediments of the Loveland Canyon were altered to quartz schists. There are numerous contemporary dikes and sills of granite and pegmatite intersecting all of the area. Later dikes of both acid and basic character cut the pre-Cambrian rocks in many places, and flows of andesite and some breccia cover a small portion of the granite and schist. Faults, although probably common, are not readily identified in the granites; other faults associated with the schist, and mostly in the areas adjacent to the foothills, are well defined and have influenced the location of minor drainage features.

THE CORRELATION OF THE LOWER ALLEGHENY[1]-POTTSVILLE SECTION IN WESTERN PENNSYLVANIA[2]

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ABSTRACT

The reports of the Second Pennsylvania Geological Survey covering the region along the Beaver River and its tributaries in Lawrence, Mercer, and Butler counties, show that the average interval between the Vanport limestone of the Allegheny group and the Homewood formation (sandstone), the youngest member of the Pottsville series is 50 feet. In the Foxburg quadrangle along the Allegheny River, the average interval is 120 feet from the Vanport limestone down to what is called the Homewood sandstone in that folio.

The present writer, however, concludes that the Upper Connoquenessing and Homewood sandstones of the Beaver River section are equivalent to the Homewood and Clarion sandstones of the Allegheny River section. The Pottsville series of the Foxburg folio should, therefore, be extended to include the Clarion formation of the Allegheny group and the Clarion sandstone should be regarded as the top member of the Pottsville series in the Allegheny River section. A study of the same members between Mayport near the eastern margin of the Clarion quadrangle and Brookville in Jefferson County, suggested that the Craigsville coal of the Foxburg-Clarion folio is the equivalent of the Brookville coal near Brookville.

INTRODUCTION

In the Pennsylvania Second Geological Survey reports of the region along the Beaver River and its tributaries in Lawrence, Mercer, and Butler counties (see map, Fig. 1) the average interval from the Vanport Limestone (Allegheny) down to the Homewood sandstone, which is the top of the Pottsville formation in that region, is 50 feet. In the more recent Foxburg-Clarion folio[3] which relates to the region along the Allegheny River, the interval from the Vanport limestone down to the supposed top of the Pottsville series, the uppermost member of which is called the

[1] Series, group, and formation as used at the present time by the Pennsylvania Topographic and Geological Survey have been adopted in this report.

[2] Published by permission of the director, Pennsylvania Topographic and Geologic Survey.

[3] E. W. Shaw, E. F. Lines, and M. J. Munn, *U.S. Geol. Survey, Geol. Atlas*, Foxburg-Clarion folio (No. 118), 1911.

Homewood formation (formerly thought to be the equivalent of the Homewood sandstone of the Beaver River section), the average interval is about 120 feet (Table I).

The problem was called to the writer's attention in the spring of 1921 and the field work which forms the basis of this report was carried on for the Topographic and Geological Survey Commission

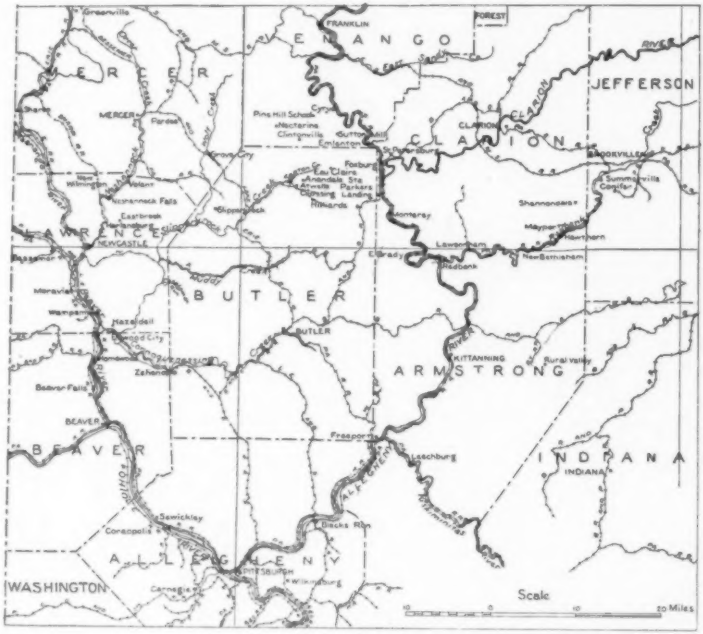


FIG. 1.—Map of western Pennsylvania

of Pennsylvania in the summer of 1921. The writer wishes to acknowledge his indebtedness to Dr. George H. Ashley and Dr. David White for many helpful suggestions and for the assistance rendered by them during their two-day visit to the field. The illustrations were prepared by the Pennsylvania Topographic and Geological Survey.

These strata were first studied along the Beaver River and some of its tributaries, after which Slippery Rock Creek was traversed

TABLE I

Correlation Chart

Beaver Valley Standard Section*				Allegheny Valley Butte-Shaw Section†				Western Pennsylvania Standard Section			
Name	Average Thickness in Feet		Interval to Vanport Limestone	Name	Average Thickness in Feet		Interval to Vanport Limestone	Name	Average Thickness in Feet		Interval to Vanport Limestone
		Coals				Coals				Coals	
Clarion group of the Lower Productive measures (mostly shale)	60‡	.....	.....	Lower part of the Allegheny formation (mostly shale)	65‡	.....	.....	Clarion formation of the Allegheny group (mostly shale)	60‡	.....	.....
Ferriferous (Vanport) limestone	15	.....	.....	Vanport limestone	5	.....	.....	Vanport limestone	10	.....	.....
Scrubgrass coal	.....	1	0 to 10	Upper Clarion coal	.....	2	2 to 30	Upper Clarion coal	.....	1½	0 to 30
Clarion coal	.....	1½	15 to 45	Lower Clarion coal	.....	2	25 to 50	Lower Clarion coal	.....	1½	15 to 50
Brookville coal	.....	2	40 to 65	Craigsville coal	.....	1½	55 to 70	Brookville coal	.....	1½	40 to 70
Beaver River group of conglomerate measures	.....	.....	.....					Beaver River group of Pottsville Series			
Homewood sandstone	30	.....	40§ to 70	Clarion sandstone	30	.....	45 to 75	Homewood formation	30	.....	40§ to 75
Mercer Shales Containing "Tionesta," Upper and Lower coals, two thin limestones, iron ore, and shale. Lower coal	30‡	 2	50§ to 95 115‖ to 140	Shales Containing a number of thin coal seams. Near the base the Brookville coal	35‡	 1	65 to 110 110 to 130	Mercer formation Shales containing "Tionesta," Upper and Lower coals, two thin limestones, and iron ore. Lower coal	30	..... 1½	50§ to 110 110‖ to 140
				Pottsville formation							
Connoquenessing sandstone Upper Connoquenessing sandstone	40	.....	70§ to 155	Homewood sandstone	35	.....	115 to 155	Connoquenessing formation Upper Connoquenessing sandstone	40	.....	70§ to 155
Quakertown shales containing Quakertown coal and iron ore	30‡	• ½	130 to 180	Mercer shale locally contains one or more thin coals	20‡	.....	120 to 185	Quakertown shales containing Quakertown coal and iron ore	25‡	.....	120 to 185
Lower Connoquenessing sandstone	30	.....	150 to 195	Connoquenessing sandstone	35	.....	165 to 200	Lower Connoquenessing sandstone	30	.....	150 to 200
Unconformity				Unconformity				Unconformity			
Cuyahoga shale of Mississippian system				Burgoon sandstone (Pocono group) of Mississippian system				Mississippian			

* I. C. White, "Beaver River District," *Pennsylvania Second Geol. Survey Rept. Q*, 1876; I. C. White, "Geology of Lawrence County," *Pennsylvania Second Geol. Survey Rept. QQ*, 1877; I. C. White, "Geology of Mercer County," *Pennsylvania Second Geol. Survey Rept. QQQ*, 1878.

† Charles Butte, *U.S. Geol. Atlas*, Kittanning folio (No. 115), 1904. E. W. Shaw, E. F. Hines, and M. J. Munn, *U.S. Geol. Survey Geol. Atlas*, Foxburg-Clarion folio (No. 178), 1911.

‡ Including coal beds. § Considerably below the average due to somewhat abnormal section near Eckerts Bridge (see section 61).

‖ Lower Mercer coal unexposed and probably absent in Eckerts Bridge (Section No. 61).

to its headwaters at the Beaver-Allegheny divide. On the east side of the Beaver-Allegheny divide the same section was then studied along the Allegheny River and its tributaries southward across the Foxburg quadrangle to the mouth of Redbank Creek in the Kittanning quadrangle. Some of the sections exposed along this traverse are seen in Figures 2 and 3, and the results of the work in this area are fairly conclusive. Several days were spent in examining the same rocks between the eastern margin of the Clarion folio and Brookville in Jefferson County (Fig. 4), but it probably will be necessary to map this area in detail before a satisfactory correlation can be obtained in this region.

The individual members where exposed were traced in detail along the outcrop and the sections were measured with a hand level and rule, using the Vanport limestone as a key-bed. The Vanport limestone is present throughout most of the region studied, but in those localities where it is absent some persistent coal was used for an index-bed.

The only members which carry marine organisms are the limestones, but where these are present they are so distinctive that paleontological evidence is not necessary for establishing the stratigraphic position of the limestone in question. The sandstones and shales are non-marine, probably in part of deltaic origin, and the only fossils which they were observed to contain are plants.

Variability in thickness within short horizontal distances characterizes the members of the Pennsylvanian system in this area and the thinning or total absence of a member is compensated by a thickening of the underlying or overlying member, or both, so that in general the interval between members is fairly constant (Table I). The standard section for western Pennsylvania is given in column 3 of the correlation chart.

The rocks have a general southward dip of about 25 feet to the mile, but this monoclinal dip is interrupted by a series of very gentle folds, which have a general northeast-southwest trend and which gradually increase in intensity toward the east.

† Charles Butte, *U.S. Geol. Atlas*, Kittanning folio (No. 115), 1904. E. W. Shaw, E. F. Hines, and M. J. Munn, *U.S. Geol. Survey Geol. Atlas*, Foxburg-Clarion folio (No. 175), 1911.

‡ Including coal beds.

§ Considerably below the average due to somewhat abnormal section near Ecketts Bridge (see section 61).

‖ Lower Mercer coal unexposed and probably absent in Ecketts Bridge (Section No. 61).

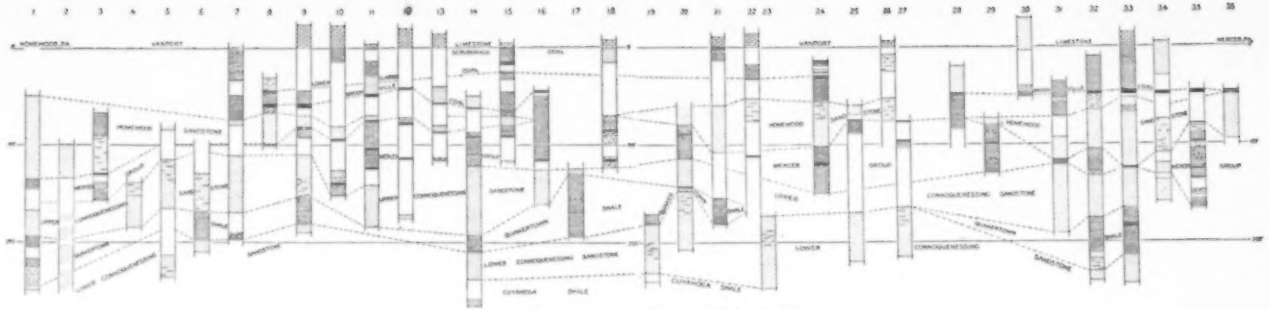
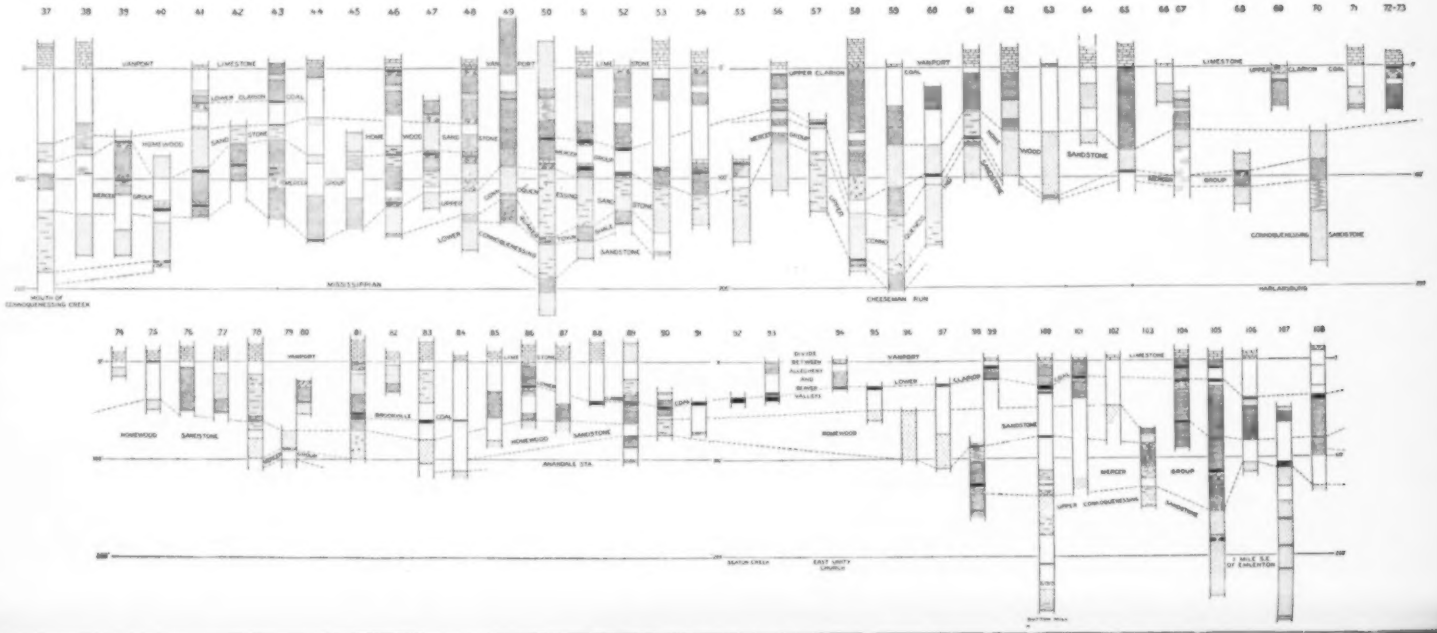


FIG. 2.—Sections between Homewood and Mercer



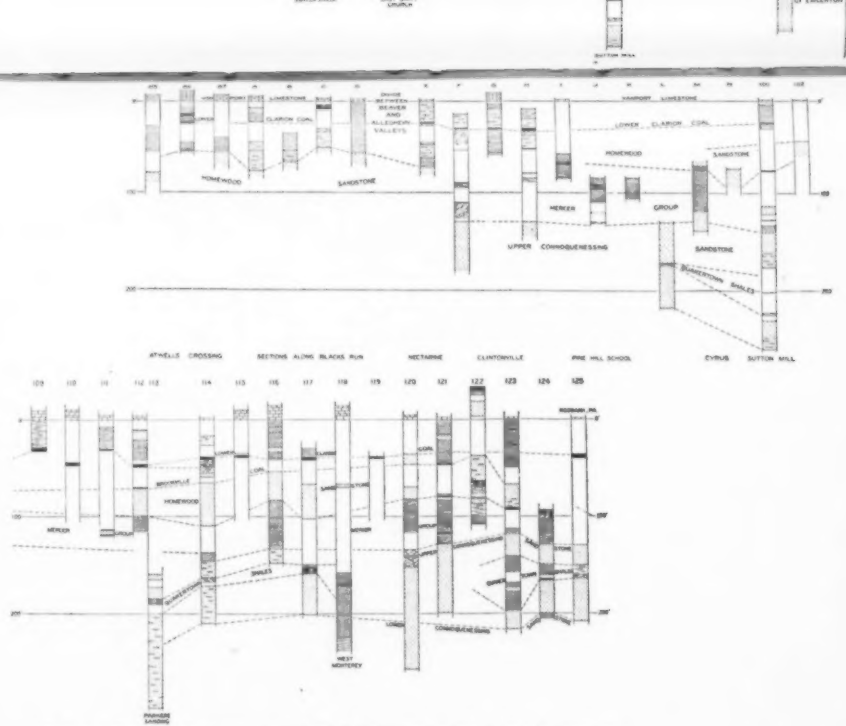


FIG. 3.—Sections between mouth of Connoquenessing Creek in Beaver River Valley and mouth of Redbank Creek in Allegheny River Valley.

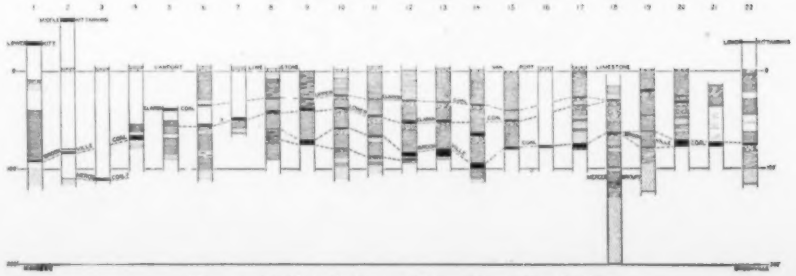


FIG. 4.—Sections between Mayport and Brookville

LOCATION OF SECTIONS BETWEEN HOMEWOOD AND MERCER (FIG. 2)

1, Mouth of Clark's Run, Homewood Station. 2, Mouth of Thompson's Run. 3, Bellton. 4, ½ mile S.E. of Koppel. 5, West Ellwood Junction. 6, ¼ mile N. of No. 5. 7, Opposite mouth of the Connoquenessing Creek. 8, 1¾ miles S.E. of Chewton. 9, 1½ miles S.E. of Chewton. 10, ¼ mile S. of Wampum. 11, Edward's Run and Moravia (De Wolf). 12, N. of Moravia (De Wolf). 13, ½ mile N. of No. 12 (De Wolf). 14, Lower part of Hickory Run (De Wolf). 15, Upper part of Hickory Run (De Wolf). 16, ¾ mile S. of Newcastle Junction. 17, ¼ mile N. E. of New Castle Junction. 18, ¾ mile E. of Mahoningtown. 19, 1 mile N.E. of Mahoningtown. 20, 1¾ miles N.E. of New Castle. 21, ¾ mile N.E. of 20. 22, 1 mile W.S.W. of Eastbrook Station. 23, Eastbrook Station. 24, 2¼ miles N.N.E. of Coaltown. 25, ½ mile N.N.E. of Neshannock Falls. 26, 1 mile N.N.E. of Neshannock Falls. 27, Same as 26. 28, 1 mile S. of Volant. 29, ½ mile S.W. of Volant. 30, ¼ mile W. of Volant. 31, ½ mile N. of Volant. 32, Drake 2½ miles S.W. of Leesburg Village. 33, 3 miles E. of Leesburg Village. 34, 1 mile N.E. of Leesburg Station. 35, Hell's Hollow, 2 miles W. of Mercer. 36, 1 mile N.E. of Mercer Courthouse.

LOCATION OF SECTIONS BETWEEN THE MOUTH OF CONNOQUENESSING CREEK IN BEAVER RIVER VALLEY AND MOUTH OF REDBANK CREEK IN ALLEGHENY RIVER VALLEY (FIG. 3)

37, 1 mile W. of Ellwood City Courthouse. 38, ¾ mile S.E. of Ellwood City Courthouse. 39, ½ mile S.E. of Ellwood City Courthouse. 40, Connoquenessing Creek, ¼ mile above mouth of Slippery Rock Creek. 41, Bluff at Wurtemburg. 42, Wurtemburg iron bridge 3 mi. E.N.E. of Ellwood City Courthouse. 43, 1 mile N.E. of Wurtemburg bluff. 44, 1 mile N. of Wurtemburg. 45, 1¼ miles N. of Wurtemburg bluff. 46, 1¾ miles N. of Wurtemburg. 47, 2½ miles N. of Wurtemburg. 48, 2½ miles N.N.E. of Wurtemburg. 49, ¼ mile N.E. of Armstrong Bridge and ½ mile S.W. of Harrison Bridge. 50, 2 miles W.N.W. of Mountville Church. 51, ½ mile N.E. of 50. 52, 1 mile S.S.W. of mouth of Cheeseman Run. 53, ⅝ mile S.W. of mouth of Cheeseman Run. 54, ⅝ mile S.W. of mouth of Cheeseman Run. 55, ⅝ mile S.W. of Cheeseman Run. 56, ¼ mile S.W. of mouth of Cheeseman Run. 57, ⅛ mile S.W. of mouth of Cheeseman Run. 58, Opposite the mouth of Cheeseman Run. 59, Along road N. from Cheeseman Run. 60, Along road N.W. from Eckerts Bridge. 61, ½ mile N.E. of mouth of Cheeseman Run. 62, ⅛ mile S. of McConnells Mills. 63, Along road N. and E. from McConnells Mills. 64, Along road S. from Rose Point. 65, Rose Point. 66, ½ mile N.E. of Rose Point. 67, ½ mile N.E. of Rose Point. 68, Kennedy Mill. 69, ½ mile N.E. of Harlansburg. 70, 1½ miles S.E. of Harlansburg. 71, ⅝ mile S. of Elliot Mill. 72, Taylor Run, 1 mile W. of Elliot Mill. 73, Taylor Run, 1 mile W. of Elliot Mill. 74, ¾ mile S.E. of Moore's Corners. 75, Mouth of Wolf Creek. 76, 1⅝ miles E. of Moore's Corners. 77, 1¾ miles W.S.W. of Moore's

Corners. 78, Dougherty's Mill. 79, Keister's Mill. 80, ¼ mile E. of Keister's Mill. 81, ⅛ mile N. of Coaltown. 82, ½ mile S.E. of Bovard. 83, Along road W. from Bovard. 84, ⅛ mile N.E. of Newhope Church. 85, ⅞ mile W. of Atwell's Crossing. 86, ½ mile N. of Atwell's Crossing. 87, 1 mile N.E. of Atwell's Crossing. 88, ¼ mile S.W. of Anandale Station. 89, 1 mile N. of Anandale Station. 90, ¾ mile W.N.W. of Anandale Station. 91, Deegan Goff Station. 92, ½ mile N.E. of Deegan Goff Station. 93, ⅞ mile E. of Deegan Goff Station. 94, ⅝ mile N. of Cherry Valley School. 95, ⅞ mile N.E. of Cherry Valley School. 96, 1 mile E. of East Unity Church. 97, ⅝ mile N.W. of Crawford's Corners. 98, 1 mile N.W. of Crawford's Corners. 99, 1 mile E.N.E. of Eakin Corners. 100, Between Sutton Mill and Lisbon. 101, 1½ miles S.W. of Dotter. 102, Crossroads 1 mile S. of Dotter. 103, 1¾ miles S. of Dotter. 104, 1 mile N.E. of Emlenton (*U.S. Geol. Survey Bull. 454*, Pl. VI, Sec. 1). 105, 1 mile S. of Emlenton (*U.S. Geol. Survey Bull. 454*, Pl. VI, Sec. 2). 106, 1¼ miles E.S.E. of Emlenton. 107, 1¼ miles N. of Foxburg. 108, ¾ mile N.N.E. of Foxburg. 109, 1½ miles S.S.W. of Foxburg. 110, 2½ miles S.S.E. of Foxburg. 111, ¾ mile N.W. of Parker's Landing. 112, ½ mile N.W. of Parker's Landing. 113, Bluff at Parker's Landing. 114, 1¼ miles S. of Parker's Landing. 115, ¾ mile N. of West Monterey. 116, ¾ mile W. of West Monterey. 117, Binker Valley, ⅝ mile S. of West Monterey. 118, ½ mile S.E. of West Monterey. 119, ½ mile E. of Upper Hillville. 120, ⅝ mile S. of Lower Hillville. 121, ⅞ mile S.S.W. of Lower Hillville. 122, ½ mile S.E. of Catfish. 123, 1½ miles E. of bridge at East Brady. 124, 2 miles E. of East Brady. 125, 2¾ miles E. of East Brady.

A, 2 miles N. of Atwell's Crossing. *B*, 2½ miles N.N.E. of Atwell's Crossing. *C*, 3½ miles N. of Atwell's Crossing. *D*, 4½ miles N. of Atwell's Crossing. *E*, ½ mile E. of Nectarine. *F*, ½ mile W. of Clintonville Crossroads. *G*, ½ mile E. of Clintonville Crossroads. *H*, ½ mile N. of Clintonville Crossroads. *I*, 1½ miles N.E. of Clintonville Crossroads. *J*, Pine Hill School. *K*, ⅝ mile W. of Cyrus. *L*, ¾ mile N.W. of Cyrus. *M*. Road W. from Cyrus. *N*, Road S. from Cyrus.

Location of Sections, Mayport to Brookfield (Fig. 4)

1, ½ mile N.N.W. of Mayport. 2, Langville. 3, 1 mile N. of Langville. 4, Reitz Run (W. G. Platt). 5, 1½ miles W.S.W. of Summerville. 6, ⅝ mile W. of Summerville. 7, ½ mile W. of Summerville. 8, ½ mile N. of Summerville. 9, 1¼ miles N.N.W. of Summerville. 10, 2 miles N.W. of Summerville. 11, 2½ miles N.W. of Summerville. 12, 2½ miles N.N.W. of Summerville. 13, 2½ miles N.N.W. of Summerville. 14, 2½ miles N.N.W. of Summerville. 15, 1 mile E. of Summerville. 16, 1½ miles N.E. of Summerville at Baxter. 17, ½ mile E. of Conifer R.R. station. 18, ½ mile E. of Conifer R.R. station. 19, 1 mile E. of Conifer R.R. station. 20, 1 mile N. of Conifer R.R. station. 21, 2 miles S.W. of Brookfield. 22, Road leading S. from Brookfield.

ALLEGHENY GROUP[1]

Above the Beaver River group of the Pottsville series, there are about 300 feet of interbedded shales, coals and thin limestones with occasional beds of more or less argillaceous sandstone. These rocks have been called the Allegheny series,[1] Formation XIII,[2] Lower Productive Coal Measures,[3] Allegheny River series,[4] and Allegheny formation,[5] the last name being used in the more recent United States Geological Survey publications. I. C. White[6] was the first to state specifically the exact limits of this "group" which he referred to as a series. He included all the strata between the top of the Pottsville series and the top of the Upper Freeport coal and divided these rocks into three subdivisions, the Freeport, Kittanning, and Clarion groups (formations of the present survey)[7] named in descending order. The Clarion group of I.C. White,[8] or Clarion formation, is the only subdivision of the Allegheny group involved in this report.

CLARION FORMATION

The shale member between the Vanport limestone and the Homewood sandstone averages 40 feet in thickness and carries three coals. Shale No. 16 of Rogers[9] averaged 20 feet in thickness and included the beds between the Vanport limestone and the Clarion coal. Later he used the name Clarion group[10] to include

[1] The names used in this report are those given in the standard section for western Pennsylvania, column 3, Table I.

[2] H. D. Rogers, *Pennsylvania Geol. Survey Fourth Ann. Rept.*, 1840, p. 169.

[3] H. D. Rogers, *Geology of Pennsylvania*, Vol. I (1858), p. 109. I. C. White, "Beaver River District," *Pennsylvania Second Geol. Survey Rept. Q*, 1876, pp. 39–40.

[4] I. C. White, "Stratigraphy of the Bituminous Coal Fields in Pennsylvania, Ohio and West Virginia," *U.S. Geol. Survey Bull. 65*, 1891, p. 9.

[5] David White, *U.S. Geol. Survey Twenty-second Ann. Rept.*, Part III, 1900–1901, p. 136.

[6] I. C. White, "Beaver River District," *Pennsylvania Second Geol. Survey Rept. Q*, 1876, p. 40.

[7] Following the present nomenclature of the Pennsylvania Topographic and Geological Survey.

[8] I. C. White, *loc. cit.*

[9] H. D. Rogers, *Pennsylvania Geol. Survey Fourth Ann. Rept.*, 1840, p. 166.

[10] H. D. Rogers, *Geology of Pennsylvania*, Vol. II (1858), Part I, p. 490.

all the rocks between the Lower Freeport sandstone and the "Tionesta," Homewood sandstone. Clarion group, as used by I. C. White,[1] included the strata from the top of the Buhrstone iron ore, which rests on the Vanport limestone, down to the top of the Homewood sandstone; this group of rocks the writer refers to as the Clarion formation.

The shales of this formation range through argillaceous, arenaceous, carbonaceous and somewhat calcareous varieties with all intermediate gradations. In many places much mica has been deposited parallel to the bedding, thus producing a pseudo-cleavage.

Interbedded with the shales are lenses of sandstone, mudstone, clay, and beds of coal. The lenticular character of these different types, the abrupt gradations both horizontally and vertically from one type of sediment to another, the abundance of horizontally truncated cross-laminations and the presence of interbedded coals are indicative of the shallow-water conditions of deposition. A brief description of the individual members of the Clarion formation follows.

The Buhrstone iron ore[2] occurs as a bed of cherty carbonate overlying the Vanport limestone, and as nodules in the shale that rests on the limestone while at the weathered outcrop limonite and hematite predominate. The unroasted carbonate ores average about 35 per cent iron; the limonite and hematite ores about 45 per cent iron.[3]

The Vanport limestone, often referred to as the Ferriferous limestone because of the Buhrstone iron ore that commonly overlies it, is an extremely pure, highly fossiliferous marine member averaging 10 feet in thickness and attaining a maximum of 25 feet. The crushed stone is utilized extensively for road-building and was

[1] I. C. White, "Geology of Mercer County," *Pennsylvania Second Geol. Survey Rept. QQQ*, 1880, p. 22.

[2] The iron-bearing horizons of the Pennsylvanian system are not "ore"-bearing at the present time in that they cannot be worked at a profit. However, for convenience of description they are referred to throughout this report as "ores," a term which might have been correctly applied to them over fifty years ago when they were economically workable.

[3] W. G. Platt, "Armstrong County," *Pennsylvania Second Geol. Survey Rept. HHHHH*, 1880, p. lxiii.

formerly much used as a flux for the Buhrstone iron ore. This limestone has long been used as a key-bed in western Pennsylvania for working out structure and stratigraphy because it is distinctive and relatively widespread.

The Clarion coal splits into two beds, giving rise to the Upper and Lower Clarion coals of Chance.[1] The Upper Clarion coal, possibly the equivalent of the Scrubgrass coal of the Beaver Valley, is from 0 to 30 feet below the Vanport limestone. In the Foxburg quadrangle, where it has been extensively worked, it is 3 feet thick. The Lower Clarion coal of the Allegheny River section, the equivalent of the Clarion coal of the Beaver River section, is from 15 to 50 feet below the Vanport limestone and separated from the Upper Clarion by shale. At some places in the Foxburg quadrangle it reaches the workable thickness of 4 feet.

The Brookville coal[2] of the Beaver River section is the equivalent of the Craigsville coal[3] of the Allegheny River sections, but it has not been proved that it is the equivalent of the Brookville coal at Brookville in Jefferson County, though they probably are correlative. In the Foxburg quadrangle this bed is of minor importance, but near Mercer it exceeds 4 feet in thickness.

POTTSVILLE SERIES

BEAVER RIVER GROUP

The Pottsville rocks constitute the basal beds of the "coal measures" in the Appalachian field. These rocks have been referred to as Seral conglomerate,[4] Pottsville conglomerate or Formation XII,[5] Pottsville series,[6] and Pottsville formation.[7] Beaver River

[1] H. M. Chance, "Geology of Clarion County," *Pennsylvania Second Geol. Survey Rept. VV*, 1880, p. 50.

[2] H. D. Rogers, *Geology of Pennsylvania*, Vol. II (1858), Part I, p. 490.

[3] Charles Butts, *U.S. Geol. Survey Geol. Atlas*, Kittanning folio (No. 115), 1904, p. 7.

[4] H. D. Rogers, *Geology of Pennsylvania*, Vol. I (1858), p. 109.

[5] H. M. Chance, "Northern Townships of Butler County," *Pennsylvania Second Geol. Survey Rept. V*, Part I (1879), pp. 31–34. (*Note:* Formation XII of Rogers is the equivalent of the Homewood sandstone. See *Pennsylvania Geol. Survey Fourth Ann. Rept.*, 1840, p. 169.)

[6] I. C. White, "Stratigraphy of the Bituminous Coal-fields in Pennsylvania, Ohio, and West Virginia," *U.S. Geol. Survey Bull. 65*, 1891, p. 179.

[7] David, White, *U.S. Geol. Survey Twentieth Ann. Rept.*, Part II, 1898–99, p. 775.

group, or Beaver River series,[1] is used in western Pennsylvania to designate rocks of Pottsville age. This group represents only the uppermost Pottsville of the Appalachian field and includes the strata between the top of the Homewood formation and the base of the Lower Sharon sandstone (see section below). Westward from the Beaver River toward the center of this Pottsville basin, the Pottsville series thickens due to the presence of successively older members. Less than a mile south of New Castle, the Lower Connoquenessing is separated from the underlying Cuyahoga shale (Mississippian) by an erosional unconformity.

The Sharon group is present in Pennsylvania only, west of the Beaver River, and is therefore not represented in the region studied by the writer. Chance's[2] generalized section of the Pottsville rocks or Beaver River series follows:

Homewood sandstone	30		
Mercer group	30		
Connoquenessing group	155	265 feet No. XII	
Sharon group	10		
Sharon conglomerate = (Ohio conglomerate)	40		435 feet No. XII
Sharon upper shales	30		
Sharon upper sandstone	15	170 feet	
Sharon middle shales	75		
Sharon lower sandstone	50		
Crawford upper or Cuyahoga shales (Mississippian)			

In West Virginia, Kentucky, Tennessee, and Alabama, the Lower beds of the Pottsville series appear, and in the Coosa basin, Alabama, the Pottsville strata reach a thickness of 5,500 feet. In the anthracite field of northeastern Pennsylvania, the Pottsville series is 1,200 feet thick, while in western Pennsylvania this series is less than 500 feet in thickness.

[1] I. C. White, "Beaver River District," *Pennsylvania Second Geol. Survey Rept. Q*, 1875, pp. 65–71.

[2] H. M. Chance, "Survey along the Beaver and Shenango Rivers in Beaver, Lawrence and Mercer Counties," *Pennsylvania Second Geol. Survey Rept. V*, Part II (1879), p. 225.

Though referred to as "conglomerate," the Pottsville rocks of western Pennsylvania in general are fairly massive, medium to coarse-grained sandstones, with conglomerate layers interbedded locally. Everywhere shale beds alternate with these sandstones. The Pottsville series in the states farther south contains many workable coals, but in Pennsylvania, except for a few localities, it is barren of workable coal beds.

HOMEWOOD FORMATION

The Homewood sandstone,[1] or Homewood formation, of the Beaver River section was found to be the stratigraphic equivalent of the Clarion sandstone[2] of the Allgeheny River section. This member is extremely lenticular and in some sections is entirely wanting. It averages 30 feet in thickness and attains its maximum of 85 feet at Homewood, on the Beaver River. In the Beaver Valley this member varies from conglomerate containing pebbles one-half inch in diameter through sandstones of varying degrees of coarseness into sandy shale, and very rarely it contains thin unworkable coal beds. The same is the case along the Allegheny River, except that in that region no conglomerate was found. Most beds in this member are cross laminated; the laminations are horizontally truncated and successive laminations are generally composed of different sized grains.

MERCER FORMATION

The coal bearing shale beds between the Homewood formation and the Upper Connoquenessing sandstone have been called the Tionesta group,[3] Mercer group,[4] and are now referred to as Mercer formation. This formation locally contains three, and rarely four coals, and has an average thickness of 30 feet. The youngest, or Tionesta, coal is immediately below the base of the Homewood

[1] I. C. White, "Beaver River District," *Pennsylvania Second Geol. Survey Rept. Q*, 1875, p. 67.

[2] E. W. Shaw, E. F. Lines, and M. J. Munn, *U.S. Geol. Survey Geol. Atlas*, Foxburg-Clarion folio (No. 178), 1911, p. 6.

[3] H. D. Rogers, *Geology of Pennsylvania*, Vol. II (1858), Part I, p. 489.

[4] I. C. White, "Geology of Mercer County," *Pennsylvania Second Geol. Survey Rept. QQQ*, 1880, p. 35.

"Tionesta"[1] sandstone. The two Porter coals,[2] now called Upper and Lower Mercer coals,[3] are below the "Tionesta" coal. Besides these coals the Mercer shales in the Beaver Valley contain two thin limestones and three iron shale horizons which were formerly worked. A generalized section of the Mercer formation for the Beaver Valley, according to I. C. White,[4] is given below, but at no one outcrop are all of these members represented.

		Thickness Feet	Inches
Homewood (sandstone) formation			
Mercer formation "group"	Upper Mercer iron-ore shales	0 to 20	
	Upper Mercer limestone	0 to 1	6
	Upper Mercer coal	0 to 2	
	Mercer shales	30	
	Lower Mercer iron ore		2 to 6
	Lower Mercer limestone	0 to 3	
	Lower Mercer coal	0 to 4	
	Lower Mercer iron ore shales	0 to 30	
Upper Connoquenessing sandstone			

The iron ore of the Mercer formation exists both as a carbonate bed overlying the limestone, and as nodules in the shale. At a number of places in the Beaver Valley these shales were formerly of considerable economic importance.

The Upper and Lower Mercer limestones which are present in the Beaver Valley, but which are entirely wanting in the Allegheny Valley, had been previously referred to by Rogers[5] as the Mahoning and Mercer limestones, respectively, and by Lesley and Lesquereux[6] as the Upper and Lower Wurtemburg limestones, respectively.

[1] The name "Tionesta" was used by the First Pennsylvania Survey to designate a group, a sandstone member and a coal bed, but the Second Pennsylvania Survey abandoned this name because of the belief that it had been incorrectly applied in various sections in the Allegheny Valley.

[2] H. D. Rogers, *op. cit.*, p. 565.

[3] I. C. White, "Geology of Lawrence County," *Pennsylvania Second Geol. Survey Rept. QQ*, 1877, p. 54.

[4] I. C. White, "Geology of Mercer County," *Pennsylvania Second Geol. Survey Rept. QQQ*, 1880, p. 35.

[5] H. D. Rogers, *Geology of Pennsylvania*, Vol. II (1858), Part I, p. 489.

[6] Lesley and Lesquereux, "Special Report on Petroleum of Pennsylvania," *Pennsylvania Second Geol. Survey Rept. J*, 1875, p. 96.

They are dark, bluish-gray, massive, and highly fossiliferous. Rarely are the two limestones exposed in any one section.

The Upper Mercer coal is of no economic importance, while the Lower Mercer coal reaches 4 feet in thickness near Mercer, and $4\frac{1}{2}$ feet in thickness in one locality in the Foxburgh-Clarion quadrangle where it is called the "Brookville" coal. The "Tionesta" coal[1] when present is immediately below the Homewood "Tionesta" sandstone and at several places along the Beaver it was impracticable to distinguish this coal from the Upper Mercer bed.[2]

CONNOQUENESSING FORMATION

The Connoquenessing formation, or Connoquenessing sandstone,[3] takes its name from the creek in Lawrence County by that name and it is thought to be the equivalent of the Massillon[4] sandstone of Ohio. In western Pennsylvania this formation is 110–150 feet thick which I. C. White[5] divided into the three following members:

Connoquenessing sandstone	Upper Connoquenessing sandstone
	Middle Connoquenessing or Quakertown shales
	Lower Conoquenessing sandstone

The Upper Connoquenessing sandstone, which is at the base of the Mercer formation, is mostly massive, but much is flaggy and thin-bedded. It differs from the Homewood sandstone in that it is essentially free from conglomerate, and where the Homewood sandstone is non-conglomerate, the writer found it impossible to differentiate between the Homewood and Upper Connoquenessing sandstones, though the former is usually more massive. The average thickness of this member is 40 feet, and locally it is sufficiently pure to be quarried as a glass sand. Along the Allegheny

[1] H. D. Rogers, *Geology of Pennsylvania*, Vol. II (1858), Part I, pp. 562, 565.

[2] J. P. Lesley and B. V. d'Invilliers, *Geology of Pennsylvania*, Vol. VIII (1895), Part I, p. 1914.

[3] I. C. White, "The Beaver River District," *Pennsylvania Second Geol. Survey Rept. Q*, 1875, p. 67.

[4] J. S. Newberry, "Geology of Stark County," *Ohio Geol. Survey Rept.*, Vol. III (1878), p. 151.

[5] I. C. White, *loc. cit.*

River the Upper Connoquenessing is erroneously called the Homewood sandstone.

The Quakertown shales, which occupy the interval between the Upper and Lower Connoquenessing sandstones in the Beaver Valley, average 25 feet in thickness. The so-called Mercer shales of the Foxburg-Clarion folio are apparently the equivalent of this member. These shales near the top contain the economically unimportant Quakertown coal and locally carry a nodular iron-ore horizon which was worked in at least one locality.

The Lower Connoquenessing sandstone, which is referred to as the Connoquenessing sandstone in the Foxburg-Clarion folio, averages 40 feet and, except for the general absence of conglomerate, the lithologic description of the Homewood sandstone is applicable. Like the Upper Connoquenessing sandstone, this sandstone is quarried for glass-making at some localities along the Allegheny River.

Near Newcastle the Lower Connoquenessing sandstone rests on the Cuyahoga shale of the Pocono group, while in the Foxburg quadrangle the Lower Connoquenessing sandstone rests on the Burgoon, the next member above the Cuyahoga shale in the Pocono group of the Mississippian system.

That an unconformity separates the Burgoon and Lower Connoquenessing sandstone is evidenced by the total absence of the Mauch Chunk shales which are believed to have been deposited over this region. The contact between the Lower Connoquenessing sandstone and the Burgoon sandstone is indefinite because the unconformity between them is not marked, and because lithologically they are similar.

SUMMARY AND CONCLUSIONS

As a result of detailed tracing of the Pottsville and Lower Allegheny strata from the Beaver River up to and across the divide between the Beaver and Allegheny rivers and thence down the latter stream, the writer concludes that there was an error in correlating these rocks along the Allegheny River in the Foxburg-Clarion folio. In that folio the sandstone known as the Clarion is in reality the Homewood sandstone of the Beaver River section, and the

sandstone called "Homewood" in the Foxburg-Clarion folio is the Upper Connoquenessing sandstone of the Beaver River section. According to this interpretation the coal called Craigsville coal along the Allegheny River is the stratigraphic equivalent of the Brookville coal of the Beaver River section. Sufficient detailed work has not been done between the eastern edge of the Clarion quadrangle and Brookville to prove that the Craigsville coal is the equivalent of the Brookville coal at Brookville in Jefferson County.

The following facts pertain to the position of the boundary between Pottsville and Allegheny strata: The Second Geological Survey of Pennsylvania assumed the top of the Homewood sandstone to be the upper boundary of the Pottsville Series, and I. C. White[1] later defined this boundary as the horizon "where the sand rocks become harder and more massive and often pebbly, accompanied with a corresponding change in the character of the imbedded fossils." In many places the Homewood sandstone is absent and is, therefore, not a particularly desirable formation for defining a boundary; the same is the case with the Brookville coal just above the Homewood formation though it is more continuous than the latter. The Upper Connoquenessing sandstone, on the other hand, is more massive and more continuous. The greatest floral break, however, occurs in the shales just below the Lower Mercer coal.[2] Because the question of the boundary is still an open one, the writer is inclined not to depart from the boundary established by the Second Geological Survey, i.e., the top of the Homewood formation.

[1] "Stratigraphy of the Bituminous Coal Fields in Pennsylvania, Ohio, and West Virginia," *U.S. Geol. Survey Bull. 65*, 1891, p. 19.

[2] David White, personal interview.

A NEW METHOD FOR MEASURING THE OPTIC AXIAL ANGLE OF MINERALS

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ABSTRACT

A method is presented which to a large extent eliminates the errors of observation of the optic axial angle by the Michel-Lévy method. Instead of standardizing circles of reference, observations on a mineral of known 2E are made directly through the interference figure of the unknown. The method is accurate to within a degree if the known mineral and the lines on the micrometer ocular are placed exactly in the 45° position.

The optic axial angle in sections of a mineral cut at right angles to either bisectrix, when so large that the points of emergence of the axes lie outside the field of view, may be measured by the method of Michel-Lévy.[1] He used a glass disk on which was drawn a series of circles spaced to measure degrees. The amount of rotation of the section necessary to bring the isogyres from the crossed position to tangency with one of these circles is a measure of the optic axial angle. Since in this method it is necessary to use the refractive index of the glass of the objective, Wright[2] modified the formula in such a way that Mallard's constant can be used instead. In both of these methods there are two sources of error. In the first place, a slight mistake may be made in standardizing the circles of reference, but there is a much greater possibility of error in determining the exact point where the isogyre of the unknown mineral is tangent to a standard circle. The isogyre itself is not a line but a bar, in many cases of considerable width, and it is necessary to concentrate on the medial line, which is not always an easy matter. Again, the curvature of the isogyre is difficult to determine exactly, so that an intersection rather than tangency is obtained. In order to overcome such difficulties, the following modification was devised.

[1] See Albert Johannsen, *Manual of Petrographic Methods*, 1918, pp. 472–74.

[2] *Ibid.*

Instead of using a real or imaginary circle of reference, there is placed below the specimen to be examined a mineral whose accurately measured optic angle falls within the field of view. The unknown mineral is then placed above it. The isogyres of the lower mineral, AM and $A'M'$ (Fig. 1), give the locus of all points where the vibration directions are parallel to those of the nicol prisms, OX and OY. Similarly, BN and $B'N'$ give the locus of all such points in the upper mineral. Since in the 45° position these curves do not intersect, there will be a change in the directions of vibration of all rays passing from the lower to the upper mineral. As a consequence, no isogyre will be seen, and the isochromatic curves will be distorted. As the upper mineral is rotated toward the parallel position, its isogyres will approach those of the lower crystal until ultimately the two overlap at the melatopes. When this is the case, the isogyres of the lower mineral appear undistorted, and, at the melatopes, will be inclined 45° to the vibration planes of the nicols.

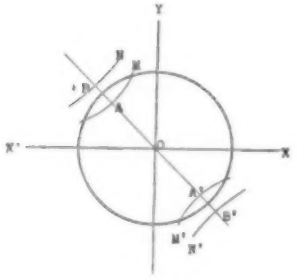

FIG. 1.—OX and OY are the vibration directions in the nicols. AA' is 2E of the known mineral. BB' is 2E of the unknown mineral.

The actual procedure for a microscope with simultaneously rotating nicols is as follows. With the nicols in the 45° position, a fragment of a crystal of known optic axial angle and of such size that it will not touch the sides of the opening in the stage, is placed immediately on top of the condensing lens under the stage. The section is rotated until the interference figure forms a cross. The nicols are now turned into the usual position, leaving the test plate in the 45° position. The mineral to be examined is then inserted, cover glass downward, over the other mineral. At first a confused interference figure will appear. The stage is now rotated until the isogyres of the lower crystal appear. By small rotations, the isogyres are brought exactly into the 45° position. This is best determined by making use of a net micrometer ocular with the striations set at 45° to the vibration directions of the nicols. The

stage reading is now noted, after which the lower mineral is thrown out and the stage rotated until the interference figure of the unknown mineral is in the form of a cross. The amount of rotation between the two positions is the angle ϕ. From this value the optic axial angle may be determined by Wright's diagram,[1] or by computation from the formula,

$$\sin E \text{ of unknown mineral} = \frac{\sin E \text{ of known mineral}}{\sqrt{\sin 2\phi}}$$

In the case of a microscope without simultaneously rotating nicols, the net micrometer eyepiece is placed in the 45° position and the known mineral is rotated until the isogyres at the melatopes are parallel to one of the directions of the net. After this adjustment the procedure is the same as before.

A suitable mineral for a standard is a cleavage flake of muscovite of a thickness to give about two wave-lengths retardation. In case the bisectrix in either of the sections is not exactly parallel to the axis of the microscope, the condition of tangency will occur at slightly different angles for each melatope. Where this happens, it is necessary to set the bar of each melatope separately to the 45° position. The average reading gives the correct rotation.

The advantages of this method are briefly these. Since the observations are made directly over a mineral of known optic angle, the possibility of error present in other methods is largely eliminated. The section of the isogyre which is being considered is very clear and distinct, and possible error in the adjustment is reduced to a minimum. By the use of the net micrometer eyepiece, the direction at the point of tangency can be determined definitely and reestablished after the insertion and rotation of the unknown mineral.

The final result will be accurate to within a degree *provided the standard mineral and especially the net micrometer ocular have been placed exactly in the 45° position.* This accurate adjustment is very important since a half-degree error in the position of the crosshairs may give an error of 4° in the value of 2E.

The following experiment gives an idea of the exactness of the method. The mineral used as a standard was muscovite with 2E,

[1] *Ibid.*, p. 473.

measured by an optic angle apparatus, 68°30′. The mineral whose angle was to be determined was topaz. The angle ϕ was determined for each melatope independently and the results averaged.

STAGE READINGS

	Melatope A	Melatope B	Crossed Position
	120°18′	121°30′	108°54′
	120°30′	120°48′	108°54′
	120°54′	120°00′	108′54°
	119°12′	121°36′	109°06′
	121°00′	120°00′	109°06′
	120°42′	120°54′	109°12′
	120°48′	121°00′	
	119°30′	121°30′	
	119°34′	121°24′	
	120°24′	121°30′	
Averages	120°17′	121° 1′	109° 1′

Average of both melatopes.....120°39′
Crossed position.....109° 1′
Angle ϕ..... 11°38′

Substituting this value for ϕ in the equation, we find it corresponds to $2E = 127°10'$. The actual value for 2E of the topaz used, as measured by an optic axial angle apparatus, was 126°46′. The error, consequently, was 24′.

REVIEWS

Geologie der Schweiz. By ALBERT HEIM. Vol. I, pp. 704, figs. 126, pl. XXIX, Leipsic, 1919; Vol. II, pp. 1018, figs. 249, pl. XXXV, Leipsic, 1922: C. H. Tauchnitz.

This is the great work of the old master, Albert Heim. Heim's classic *Mechanismus der Gebirgsbildung* appeared in 1878 and laid the foundations for much of our present understanding of structural geology. Not a few of the principles of pre-Cambrian geology were in fact first worked out in the contorted Mesozoic and Tertiary rocks of the Swiss Alps, and to Heim's early elucidation of these our science is greatly indebted. Now, more than forty years later, the ripening fruits of his long researches are given forth in this new commanding work, the *Geologie der Schweiz.*

The geology of Switzerland falls naturally under three heads in consequence of three major geologic units of the country—the interior lowlands, or region of the Molasse, the Swiss Jura to the north, and the Alps to the south. Volume I is divided into two parts, the first of which is devoted to the region of the Molasse and to the general Pleistocene geology of the whole country, while the second part treats of the Jura. Volume II, at greater length, presents in admirable fashion the complex geology of the Swiss Alps.

The Molasse is the extensive detrital formation which developed on the north border of the Alps from the degradation of the rising mountains. In age it ranges from Middle Oligocene to Upper Miocene, and comprises both marine and terrestrial phases. It is older than the folding of the Jura Mountains and participated in that orogenic movement. The folding of the Molasse, however, was essentially complete before the Pleistocene. The stratigraphy, paleontology, and tectonics of this remarkable formation, as well as the physiography of the region, are carefully described in detail.

The Jura Mountains form the northern borderland of Switzerland. They are subdivided into Plateau Jura and Folded Jura, each being discussed as separate units. The full hundred pages devoted to their general stratigraphy portray the extensive development of Mesozoic and Tertiary formations, particularly the splendid Jurassic succession of which this is the type region. Tectonically the folded range is of special interest as a thin-shelled range of unusual shallowness. This thin,

surface sheet has been driven northward, shearing over its base, by the last strong horizontal thrusting of the greater Alpine mass to the south. The Jura chains are strongly arcuate, with the movement coming from the inner side of the arcs. As the lines of forward movement diverge, the curved chains have suffered longitudinal stretching which has resulted in many transverse vertical faults. The eastern sides of these transverse faults have moved relatively northward and outward. The total shortening in kilometers is greater in the middle portion of the bent chains and diminishes toward the two extremities.

The greatest problems of all are presented by the Swiss Alps. The very extraordinary tectonic phenomena of the Alps have necessitated explanations involving heroic conceptions. Heim has sketched admirably the gradual development of these conceptions which have culminated in the astonishing decken theory. Not being an extreme deckenist, Heim has kept close to the field descriptions and the testimony of the rocks and rock structures, and has not allowed theoretical considerations to influence unduly his interpretations. Confidence is inspired throughout by the mastery of detail, the painstaking care, and the soundness of judgment which characterize the master hand.

The order of decken building and the sequence of the overthrusting movements will come as something of a revelation to many American readers who are not conversant with some of the newer advances made in Alpine studies. The diastropic sequence is now given as follows:

I. East Alpine phase, at the close of the Cretaceous. Beginning of East Alpine decken movement. Not strong.

II. Early Pennine phase or first paroxysm. Middle Oligocene. Rise of Central Massif; pushing forward of Pennine and East Alpine sheets. Miocene period which followed, relatively quiet.

III. Helvetian phase or second paroxysm. Early Pliocene. Helvetian decken moved northward. Renewed activity of Pennine and East Alpine decken. Moving onward of now passive klippen (exotic blocks). Jura folded.

IV. Insubrian phase. Close of Pliocene. Southern border of Alps sank, was underthrust, and the structures of the root region steepened. Overthrusting of Helvetian sheet to its present position. Strong uplifting of Alps in early Pleistocene.

Thus the earlier interpretation that the lower decken were formed first, and that the later sheets piled up and overrode them has not stood the test of time.

Heim accepts 200–300 kilometers as the proper order of magnitude of crustal shortening involved in the formation of the Alps. As the Alpine chains now form a belt 120–50 kilometers broad, the width of this zone before folding must have been two or three times greater than now.

The discovery of the decken structure thus makes the shortening about twice that estimated earlier on the theory of autochthonousing fold (Heim's 120 km. or 74 miles). Some of the earlier, more fantastic decken interpretations called for more excessive amounts of shortening.

From a study of Argand's profile of the Pennine sheets, the depth of folding is seen to reach down to depths of about 30 kilometers. The profile of Staub for the Graubündner Alps gave a still greater thickness of folded shell, amounting to 35–40 kilometers. Heim thinks that the folding may have extended as deep as 50 kilometers below the highest anticline of the Alps.

Considerable space is naturally devoted to discussions of the development of folds and faults and the principles of Alpine metamorphism, fields for which Heim's basal studies laid the foundations long ago. Eruptives and intrusives require less space. Then follows in succession the detailed geology of each of the great decken masses. From one hundred to two hundred pages is devoted to each group of decken. In each, the systematic stratigraphy with the leading paleontologic facts and interpretations forms the first part, while the second part is devoted to the tectonics. The excellent illustrations and remarkable cross-sections add greatly to the effectiveness of these chapters, and will be appreciated by those who read pictures more easily than German.

The Swiss master holds strongly to the contraction theory of mountain-building and the local concentration of deformation in the Alps. He says that the facts of Alpine geology will admit of no other general philosophy. It is to be noted, however, that this contraction is assigned largely to cooling rather than to molecular rearrangement under gravitative compression in favor of greater density in the interior, as urged by T. C. Chamberlin, which allows vastly greater shrinkage than can result from cooling. Furthermore we do not know that there has been any cooling of the earth's interior in Tertiary times. There are thus two species of the contraction theory. Heim distinguishes between primary and secondary deformation: Primary deformation produced by the stresses within the whole earth shell which must accommodate themselves to the shrinking core; secondary deformation produced by the weight and stresses of individual rising or existing mountain systems. These latter are the result of the primary deformations, mostly sinking through the weight of piled-up folds or eruptives, and later uplift through removal of material by erosion. Vertical isostatic movements come in here.

Heim discusses briefly but strongly the various new theories of mountain-building which have recently been urged by Ampferer, Walter Penck, Wegener, and others. His refuting of these is convincing to the reviewer.

R. T. C.

Lehrbuch der Geologie: I. Teil, Allgemeine Geologie. Zweite und dritte erweiterte Auflage. By PROFESSOR DR. F. X. SCHAFFER. Leipzig und Wien: Franz Deuticke, 1922. Pp. x+504, figs. 481.

The author of this elementary textbook has sought for simplicity and clearness by concentrating upon the essentials of the science. These essentials are treated with a fulness and vigor which give the American reader some idea of the recent developments in geologic knowledge and thinking in central Europe.

In an introductory section geology is defined, the origin and general properties of the earth are discussed, and geologic processes are classified according to the source of their energy. The main portion of the book is divided into two parts. The first describes the effects of forces originating within the earth—vulcanism, evidences of plutonic action, faulting, folding, earthquakes; the second those of surface forces—weathering, transportation, deposition, and the fossilization process. Finally there is a brief discussion of theories of mountain building, the distribution of earthquakes, and the problems of vulcanism.

Matters now in dispute among geologists are not passed over merely because they are unsettled. For instance, the Wegener hypothesis is presented (with diagrams) in this as in the 1916 edition, and its strength and weakness discussed. This is done with intention, to show geology as a living, growing science.

Throughout the book, the emphasis is upon process rather than upon product. There is no systematic discussion of igneous or metamorphic rocks, and properties of rocks which require the supervised study of specimens are intentionally omitted. Similarly there is no biologically systematic treatment of fossils, but the modes of occurrence and preservation are described at some length.

The author has made good use of his connection with the Vienna Natural History Museum, shown especially by the fact that many of the excellent diagrams and photographs are original. The photographs were taken in all parts of the world, with Southeastern Europe, Asia Minor, Northern Africa, and other Mediterranean lands best represented. The illustrations throughout are remarkably well chosen to supplement the text. As examples, there may be cited the photographs of the Wately laccolith (p. 41), block faulting along the Corinth canal (p. 119), karst topography (p. 197 and elsewhere) and karst streams (pp. 263 ff.). Perhaps the most notable portion of the book is the beautifully illustrated fifty-page section on the fossilization process.

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